

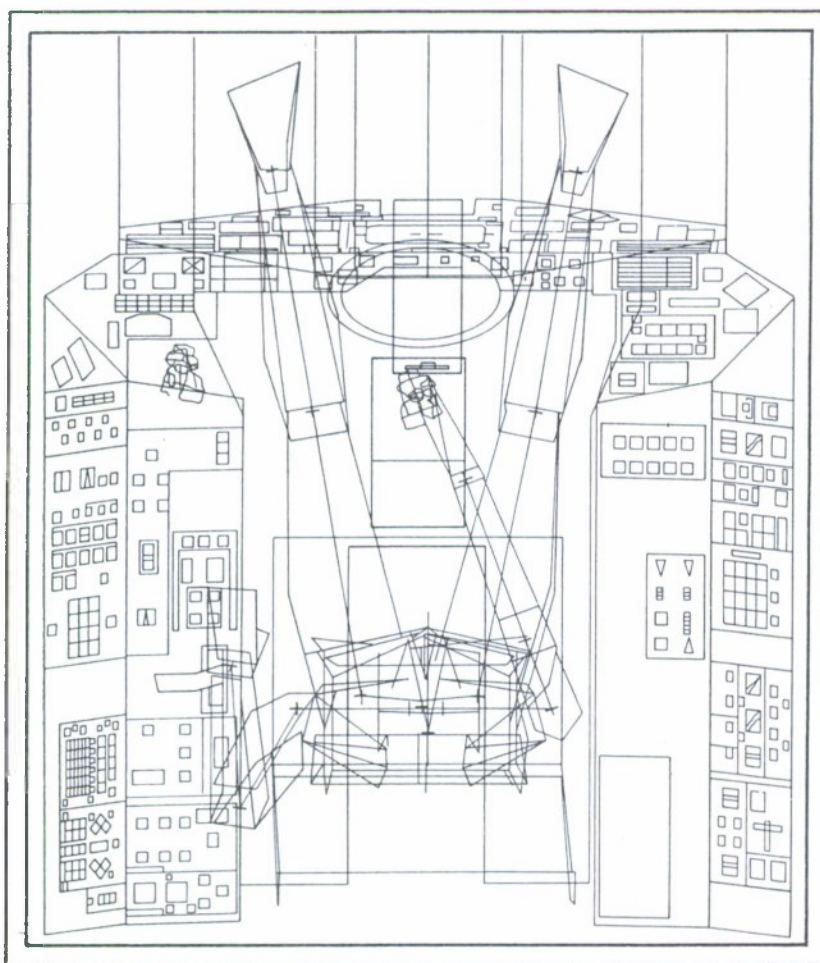
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COCKPIT GEOMETRY EVALUATIONPHASE I FINAL REPORT
VOLUME V-VALIDATION

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II	D162-10126-1	HUMAN DATA
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COCKPIT GEOMETRY EVALUATION

PHASE I

FINAL REPORT

VOLUME V-VALIDATION

Prepared for
Joint Army-Navy Aircraft Instrumentation Research Program

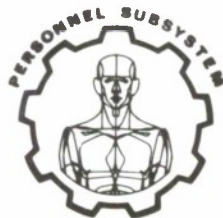
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1.0 INTRODUCTION

This report is one volume of five describing the results of the validation of the initial phase of the Cockpit Geometry Evaluation Method(s) Development Program. This program is being pursued in conjunction with the Joint Army Navy Aircraft Instrumentation Research Program Working Group (JANAIR) under Contract Number N000114-68-C-0289, NR 213-065.

The long range program objective is to develop a mathematical man-model which closely simulates the physical movement parameters of any sized human operator at any particular workstation. Such a technique will afford an improved means of evaluating the geometry of any given workstation by eliminating many of the deficiencies of current evaluation techniques.

The feasibility and adequacy (validity) of any model are to be determined by comparing the synthesized movements of the man-model with humans performing the same or similar tasks. The validation described herein was the initial attempt to perform a rigorous statistical comparison of human arm joint movements with the joint locations synthesized by the man-model. In addition to providing a part of the basis to accept or reject the mathematical model, the statistical comparisons were used for guiding the modifications incorporated during the model development.

A 23-joint link man (BOEMAN-I), shown in Figure 1, and associated mathematical techniques and computer programming for synthesizing upper torso

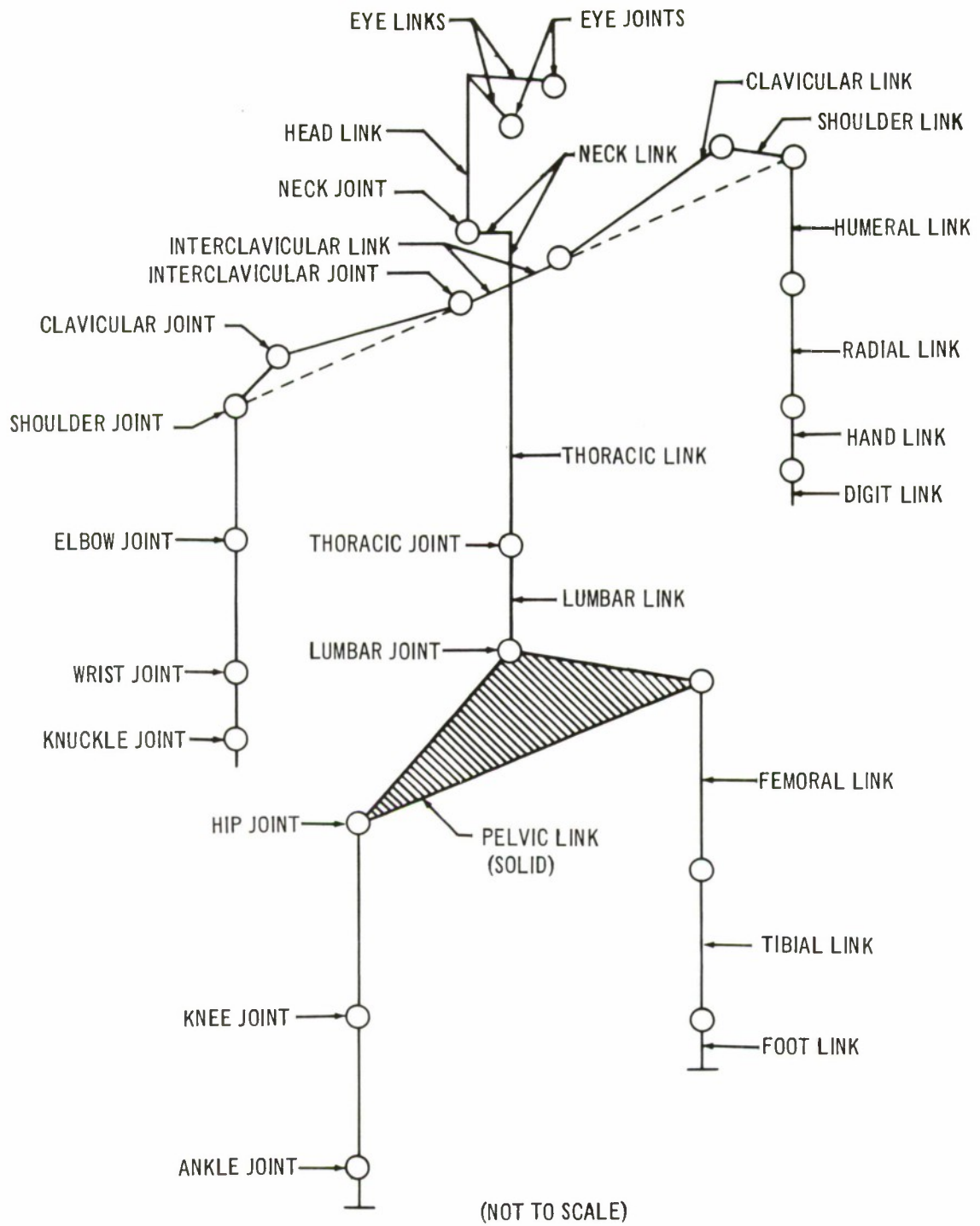


Fig. 1. BOEMAN-I Baseline Man-Model

movements were developed during the initial phase of the program. The link-man was adapted from Dempster (1)*.

*Numbers in parentheses indicate the reference listing in Section 6.0, REFERENCES.

2.0 SUMMARY AND CONCLUSIONS

A baseline man-model was provisionally validated during the first phase of the planned six-phase Cockpit Geometry Evaluation Program. This program is the first known experimental development of a three-dimensional computerized man-model; consequently criteria for validation were non-existent. It initially appeared that a rigorous criteria should be established with modifications to the criteria made as the development progressed. This allowed changes based on working experience with the model. The rigorous validation criteria held that the man-model with its adjustable link lengths must closely simulate the movement paths and the maximum reach envelopes of any sized human operator at any particular workstation. After completion of the first phase of the program, it could then be determined if the concept of a computerized man-model was feasible and if so, improved validation criteria would be determined.

Human arm movement was considered to be the most important parameter to be compared in the validation. Two types of human joint movements were recorded using a multiple camera technique. These were right arm movements and typical pilot movements. For the first type, four subjects seated in an open space performed nine right arm tasks twelve times. These tasks were designed to establish maximum reach capabilities. For the second type three subjects "flew" the Boeing Multimission Flight Simulator five times. Typical movements were selected for comparison. In addition, films of CH-46 helicopter pilots performing an actual flight test were used to

determine if the scope and variety of the two preceding efforts adequately covered movements normally required of helicopter pilots.

A combination film reader and computer card punch was used to reduce the film data for computer input. Computer programs were developed to convert these film data to three-space joint locations and determine arm link lengths.

The man-model was developed in stages. Initially the model had unlimited movement of one arm and a rigid spine. Joint angular limits were added during Stage 2, and the spine was permitted to flex during Stage 3. Stage 4 developed a link-man with unlimited movement of the complete upper torso (spine, both arms and head). Stage 5 presently under development is placing joint angular limits, compatible with human limits, on the full man-model.

A rigorous statistical analysis was developed to compare human joint locations with those synthesized by the man-model for the same task. The statistical analysis paralleled the development of the model beginning with Stage 3 and provided an iterative technique for improving the model at each stage. The statistical comparisons indicated modifications to the model. The improved model performed the same tasks and the results were statistically compared again. When no further improvements were indicated, the next stage of the model development began. The right arm movement data were used to compare and improve the model developed during Stage 3. Typical pilot movement data were used with Stages 4 and 5.

Human joints locations of only one subject at a time, and those synthesized by the man-model, were compared. Only the midpaths of the joints (shoulder, elbow, wrist and hand) were compared for each task performed. The midpath of each joint is determined by dividing, by 2, the length of the path of each joint during the first repetition of each task. This establishes a midpath plane for each joint. Successive repetitions by the subject performing the same task produced a scatter of points in these midpath planes. The midpath joint locations, synthesized by the man-model performing the same task, were compared statistically with these scatters of points. Midpath planes were chosen as part of the rigorous validation criteria since it was assumed that the greatest deviation between the man-model and human movement would occur there. In addition, during Stage 3, the maximum reach envelopes established in the right arm movements must be compatible. Ideally statistical differences would not occur under these rigid restrictions. If so, it could be concluded that a statistically valid model had been developed at each stage. More realistically, if statistical differences did occur, their practical significance would have to be evaluated.

The hand joint during Stage 3 tests reached the specified control location in all but 3 cases. In these cases synthesized hand-joint locations were within 2 inches of the control point. All Stage 3 control points were near the maximum reach capability of the subject. However, the results of approximately 70 final statistical comparisons for Stages 3 and 4 indicated that only three comparisons were found to be statistically acceptable at the 0.01 probability level.

Practically these differences appear negligible when plots of the subjects' and synthesized midpath joint locations are visually inspected. This was especially evident when the variation between different subjects performing the same task was visually inspected. This indicates that the rigorous statistical analysis used in Phase I is too restrictive. An obvious improvement to the statistical analysis would group the data of similarly sized subject performing the same task. Hence between subject variation of the general population would be considered. From a practical standpoint, it appears that:

- 1) The concept of a mathematical man-model is feasible and should be continued.
- 2) The differences between human and man-model movement appear negligible, hence the man-model has been provisionally validated.
- 3) Future efforts must continue to improve both the man-model and the validation criteria and methods.

3.0 DISCUSSION

3.1 GENERAL

A review of the literature indicated that no one has reported the development of a three-dimensional computerized mathematical man-model. Attempts to develop simplified two-dimensional models existed but they provide little if any guide to a three-dimensional model (2) (3). The only real assist was provided by Dempster (1) who developed a link-man based on human dimensions. Since the concept is a new experimental development, validation criteria were non-existent. Furthermore, data for validation also proved to be lacking. Hence, such a complex undertaking presented many unforeseen obstacles and assumptions and decisions had to be made.

High standards and goals were set to insure that the first phase effort would yield the best model compatible with the time and economic limitations. At the end of the first phase, then the feasibility of a computerized man-model could be evaluated adequately. Initially rigorous criteria were established with modifications made when indicated as the development progressed. The criteria held that the man-model must synthesize joint locations of any human performing any task. Inherent in this and perhaps more important is that the man-model must have reach characteristics identical to those of an equally sized human.

Ideally if these rigorous criteria could be met, then it could be concluded that a feasible and accurate model had been developed. Because the

3.1 GENERAL (cont.)

development is a new concept these ideals could be too restrictive. Hence, practical subjective evaluations might be required. Nevertheless a statistical comparison, based on the rigorous criteria, was developed during the initial phase. Besides providing a method for quantitative comparisons, the analysis was to provide modifications and improvements to the model. The statistical analysis was to test the hypothesis, "The joint locations of the arms synthesized by the model are identical to those of the same sized human performing the same task." These comparisons for each task were to be performed at the midpath of the arm joints where the largest discrepancies between the model and the human were likely to occur. The arm movements of the man are most complex and critical. Hence the validation efforts and the development of the man-model started with an arm system.

3.2 METHODS AND PROCEDURES

A multiple camera photographic technique was selected to determine human joint movement paths. This method provided the best available means within the time and manpower limitations of Phase I, to obtain the adequate model validation data. Data were collected under two conditions:

- 1) Four seated subjects, in an open space, performed various one-arm movements. The tasks were designed to provide

3.2 METHODS AND PROCEDURES (cont.)

midpath joint locations during maximum joint movements.

The subjects ranged in stature from 66 to 74 inches, thus providing a large range of reach capability.

- 2) Three subjects "flew" the Boeing Multimission Flight Simulator shown in Figure 2 to obtain typical upper body pilot movements. This simulator represents an advanced fighter/attack aircraft capable of VFR or IFR flight. An IFR training mission, with degraded mode operation was used.

Films of CH-46 helicopter pilots performing an actual flight test were supplied by the Vertol Division of The Boeing Company and were used to determine if the scope and variety of the two preceding validation efforts adequately covered movements normally required of helicopter pilots. A synopsis of the types of human movements obtained during phase I are presented in Table I.

A method for reducing the film data to three-dimensional space locations was developed, as well as a statistical analysis to determine the commonality between joint movement of the man-model and humans. These methods are presented in Appendices A and B respectively. Computer programs were developed to perform these functions.

Table 1. Synopsis of the Types of Human Movements Obtained During Phase I

<u>HUMAN MOVEMENTS</u>	<u>EXPERIMENTAL ENVIRONMENT</u>	<u>EXPERIMENTAL DESIGN</u>	<u>REMARKS</u>
Right Arm Movements	Cockpit seat in an open space (see Figure 5)	4 subjects 9 tasks 12 repetitions 2 70mm still cameras (1 - overhead) (1 - lateral right)	Majority of the tasks were designed to establish maximum reach capabilities of each subject.
Typical Pilot Movements	Boeing Multimission Flight Simulator (see Figure 2)	3 subjects 6 tasks 5 repetitions 3 16mm movie cameras (1 - overhead) (1 - each side)	10-minute training mission using Instrument Flight Rules. Tasks analyzed were selected from motions necessary to correct 6 system failures (degraded mode operations).
Typical Helicopter Movements	Vertol CH-46	1 subject Varied tasks 1 repetition 1 16mm movie camera (overhead and aft of pilot)	Visual inspection of typical helicopter pilot movements to determine if such movements are similar to those more thoroughly analyzed in the preceding efforts.



Fig. 2. Boeing Multimission Flight Simulator

3.2 METHODS AND PROCEDURES (cont.)

The approach to validation paralleled the development of the man-model. Initially only one-arm and torso movement was developed in the man-model. That is, the man-model contained the lumbar and thoracic links along with right interclavicular, clavicular, humeral, radial, and hand links. In performing the statistical validation, the one-arm model was compared initially with the right arm movements to provide direction for the development of a complete upper torso man-model. After successful development of the complete upper torso model (both arms, torso, and head), it was validated with the typical pilot movement data. A flow diagram of the man-model validation is given in Figure 3.

3.2.1 Right-Arm Movements

This part of the validation was instituted so that extreme reach capability comparisons could be conducted. Four seated subjects performed nine right-hand tasks. The tasks consisted of moving the right hand, from an initial position on the arm rest of a "pilot's seat", to a photocell which was rigidly attached to a floor stand. The photocell location was varied in each task and positioned such that each subject performed full-reach movements with the right hand. Some tasks required bending of the upper torso away from the seatback. Twelve repetitions of each task were performed by each subject.

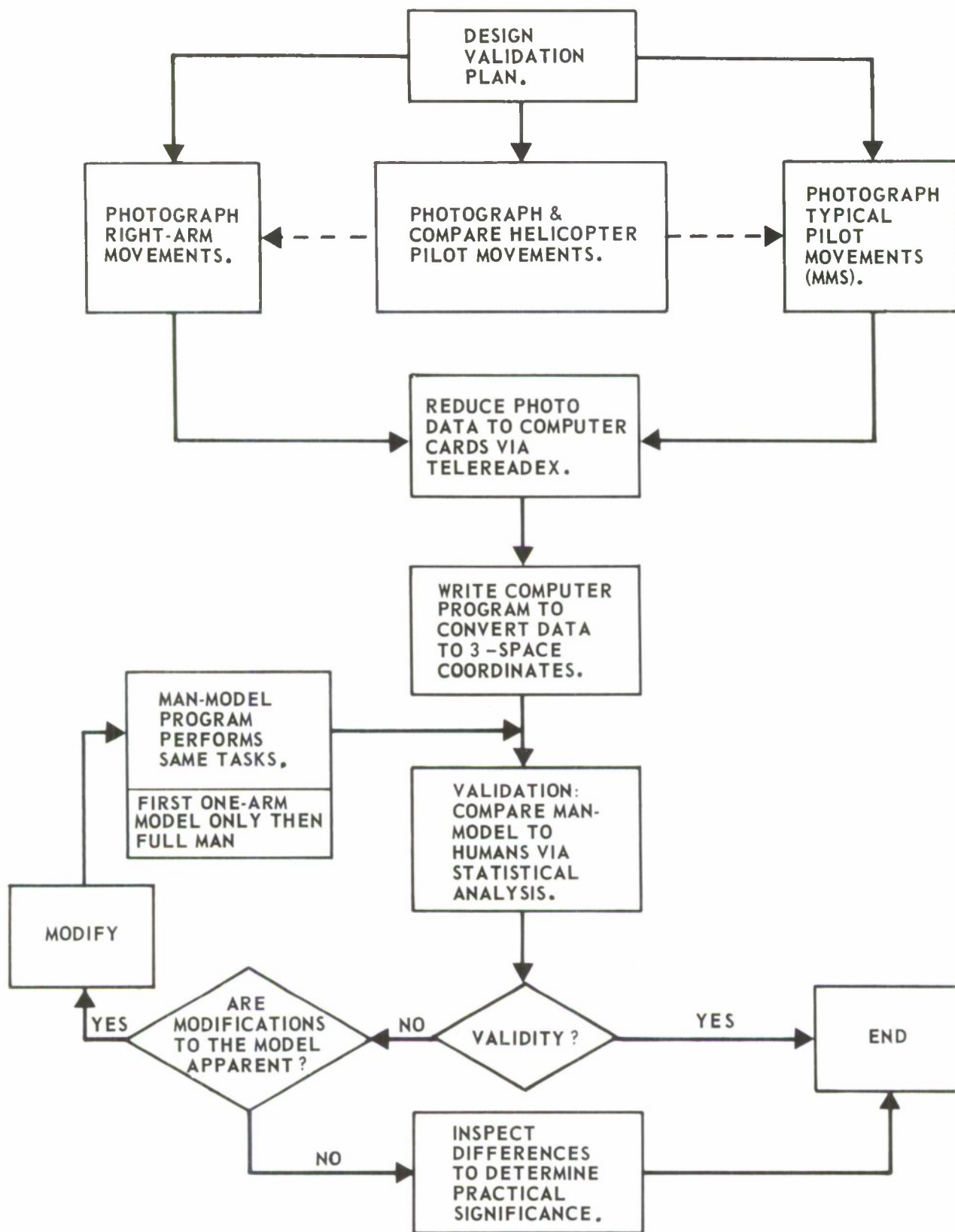


Fig. 3. Flow Diagram of the Man-Model Validation

3.2.1 Right-Arm Movements (cont.)

Two 70mm still cameras, each with an electric shutter and motor-driven film advance, were positioned with their principal axes perpendicular to each other; one overhead of the subject and the other to the right side. The intersection point of the principal axes of the cameras was in front, and to the right, of the seated subjects right shoulder. In this way, the entire right arm reach envelope could be photographed. Calibration grids were used on the floor and wall so photographic data could be transformed to Cartesian coordinates. A perspective diagram of the test configuration is shown in Figure 4 along with the convention used for identifying the coordinates. Pictures from the top and side cameras are shown in Figures 5 and 6 respectively.

To observe the excursions of the various joints in the performance of a task, flashing lights were taped on the outside of the right arm over estimated joint centers of the hand, wrist, elbow, and shoulder joints. The hand "joint" was defined as the first knuckle of the middle finger. This knuckle location was considered to be the best identifiable approximation of functional reach.

Before commencing the experimental procedure the supporting (room) lights were "on". When the cameras and subject were ready to perform the task, the supporting lights were extinguished by an observer who then turned on the experimental light circuit. This circuit consisted of the flashing

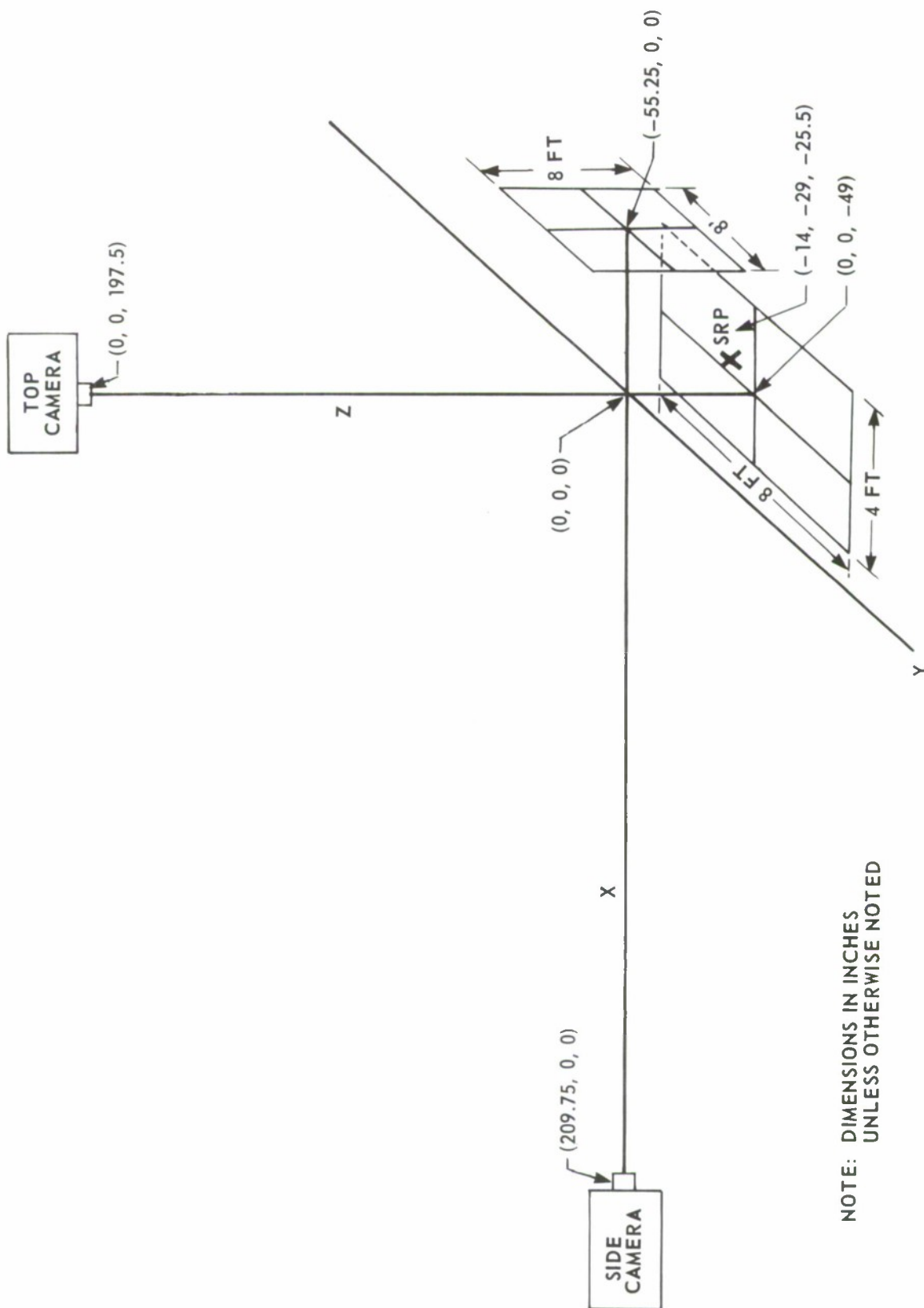


Fig. 4. Perspective Diagram of the Right-Arm Movement Test Configuration

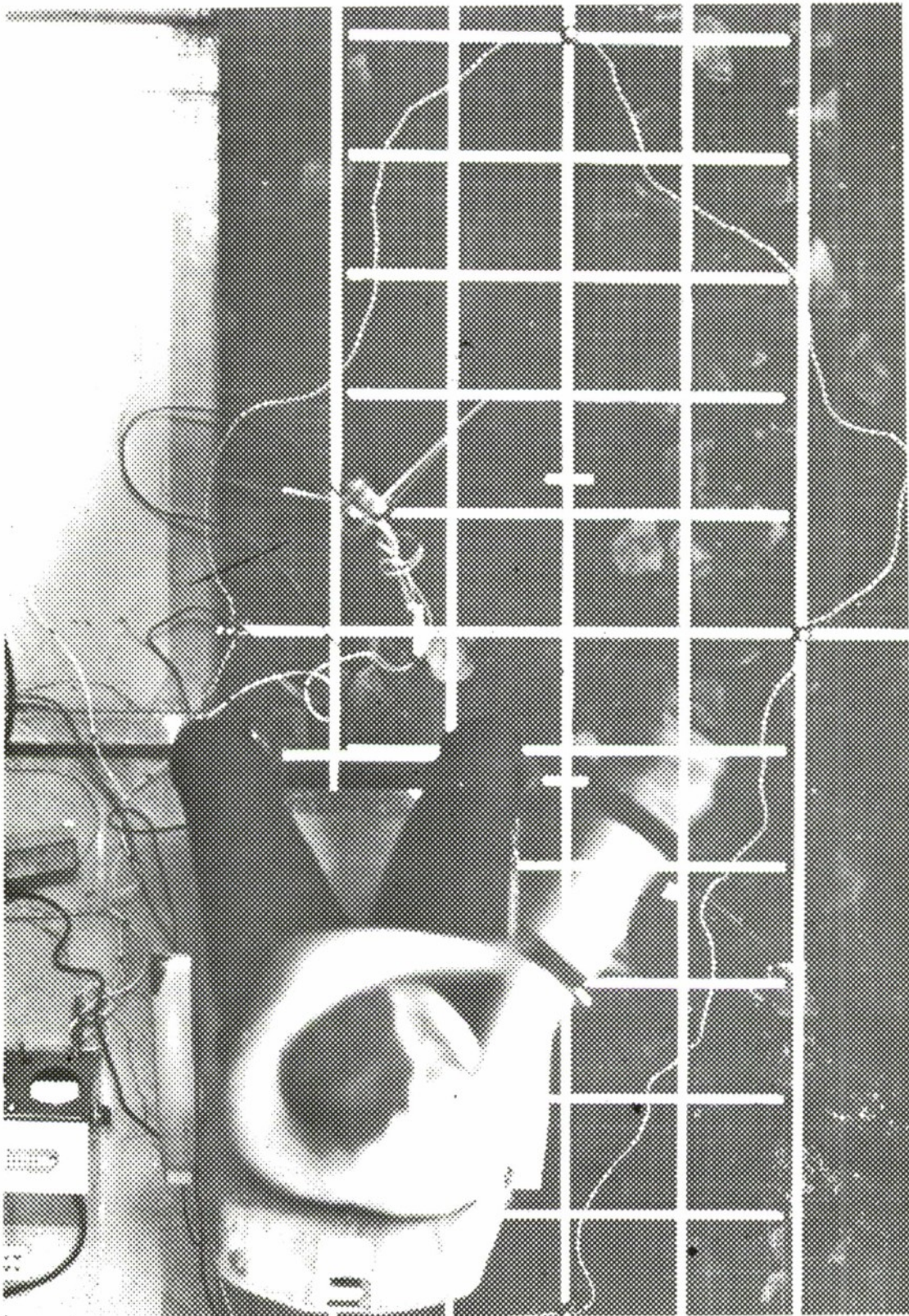


Fig. 5. Top View of the Experimental Configuration for the Right Arm Movements

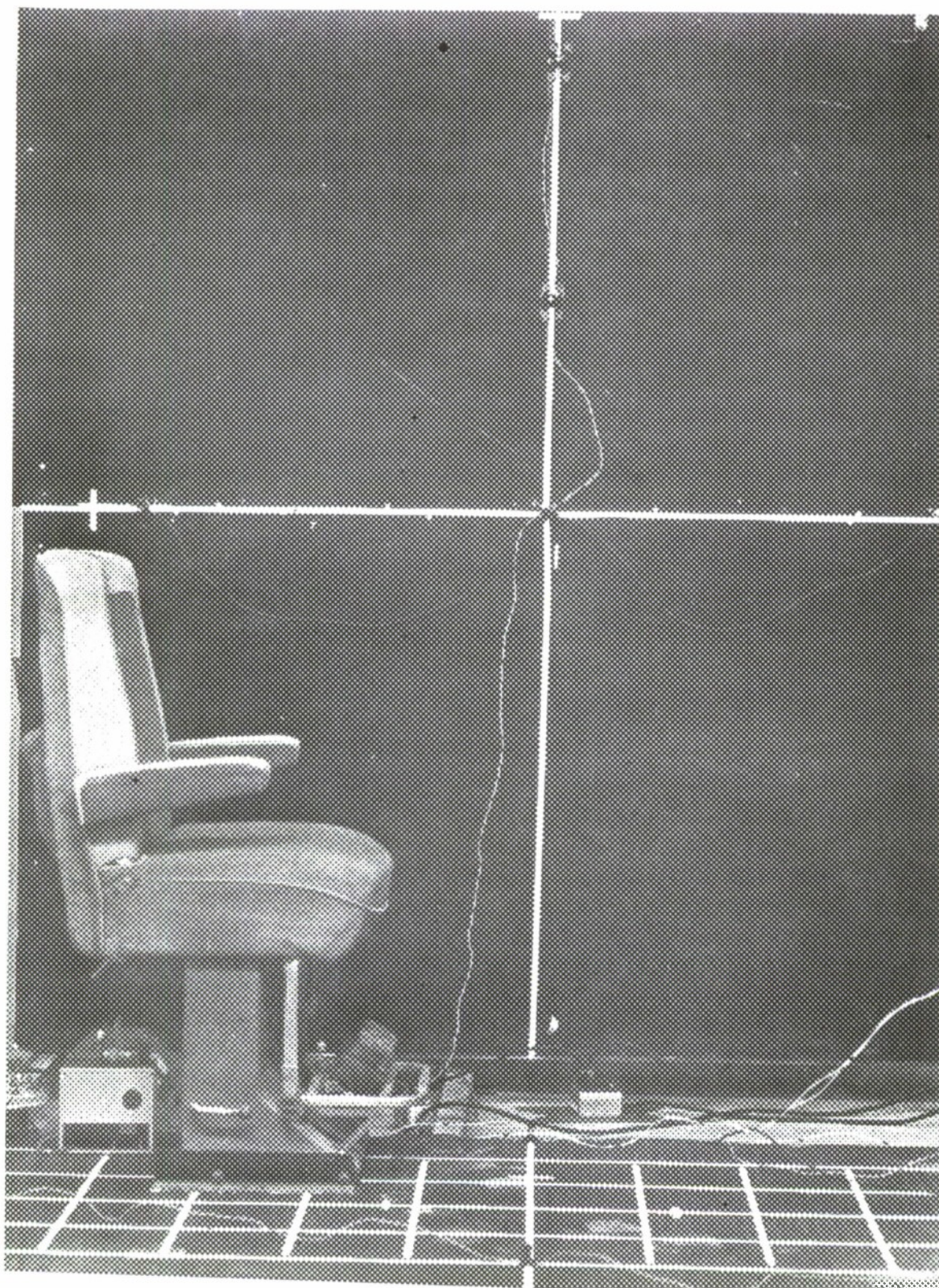


Fig. 6. Side View of the Experimental Configuration for the Right Arm Movements

3.2.1 Right-Arm Movements (cont.)

lights at the joints, the light illuminating the photocell, and lights on the calibration grids. When the subject grasped the photocell at the end of the task, the circuit, which energized the flashing lights, was interrupted. While the subject held a finger over the photocell, the observer closed the camera shutters and advanced the film in each camera. The subject then released the photocell and held momentarily until the flashing lights resumed operating and the observer opened the film shutters. The subject then returned to the original (resting) position. The observer then closed the camera shutters once more and advanced the film in both cameras. Twelve repetitions of this process were made. The observer turned on the supporting lights and extinguished the flashing lights when the subjects had completed the final repetition of each task.

The lights at the joints flashed at a rate of 8-10 flashes per second. The first frame of film in each camera recorded the joint motions from the resting position to the target and the next frame recorded the return motion from the target to the resting position. A typical film frame is shown in Figure 7. Each subject performed the twelve repetitions of the task before the next task was commenced.

3.2.1.1 Right-Arm Movement Data Reduction

The film data were reduced and transferred to computer cards through the combined use of a Tele-Readex, and a Summary Punch. Essentially, this



Fig. 7. Film Frame Showing Joint Light Traces

3.2.1.1 Right-Arm Movement Data Reduction (cont.)

consists of a combination film projector and X-Y plotter and a computer card punch as shown in Figure 8. The Tele-Readex projected a single frame onto the plotter grid. The hairlines of the plotter were centered on a known control in the cockpit to establish a constant reference for measurement. It was then positioned over the points under consideration and the system coordinates (counts) of this point (either X and Y, or Y and Z depending upon which camera the film was from) were punched on computer cards. The Tele-Readex system indicated 200 counts for each inch the hairline was displaced from the established origin, and this number for each coordinate was transferred to the cards. Between 6 and 9 points were read on each joint trace.

In addition to the coordinates, the subject, view, repetition, task number, joint, and point number were punched on each data card. These data, combined with the relationship between the calibration-light distances and the units of the system, were later used as input data to the computer program to convert the film data to true three-space Cartesian coordinates.

The computer program for the right arm movements converted the joint excursion data contained on the computer cards to three-space locations by using the equations developed in Appendix A. An abbreviated flow diagram of this program is given in Figure 9.

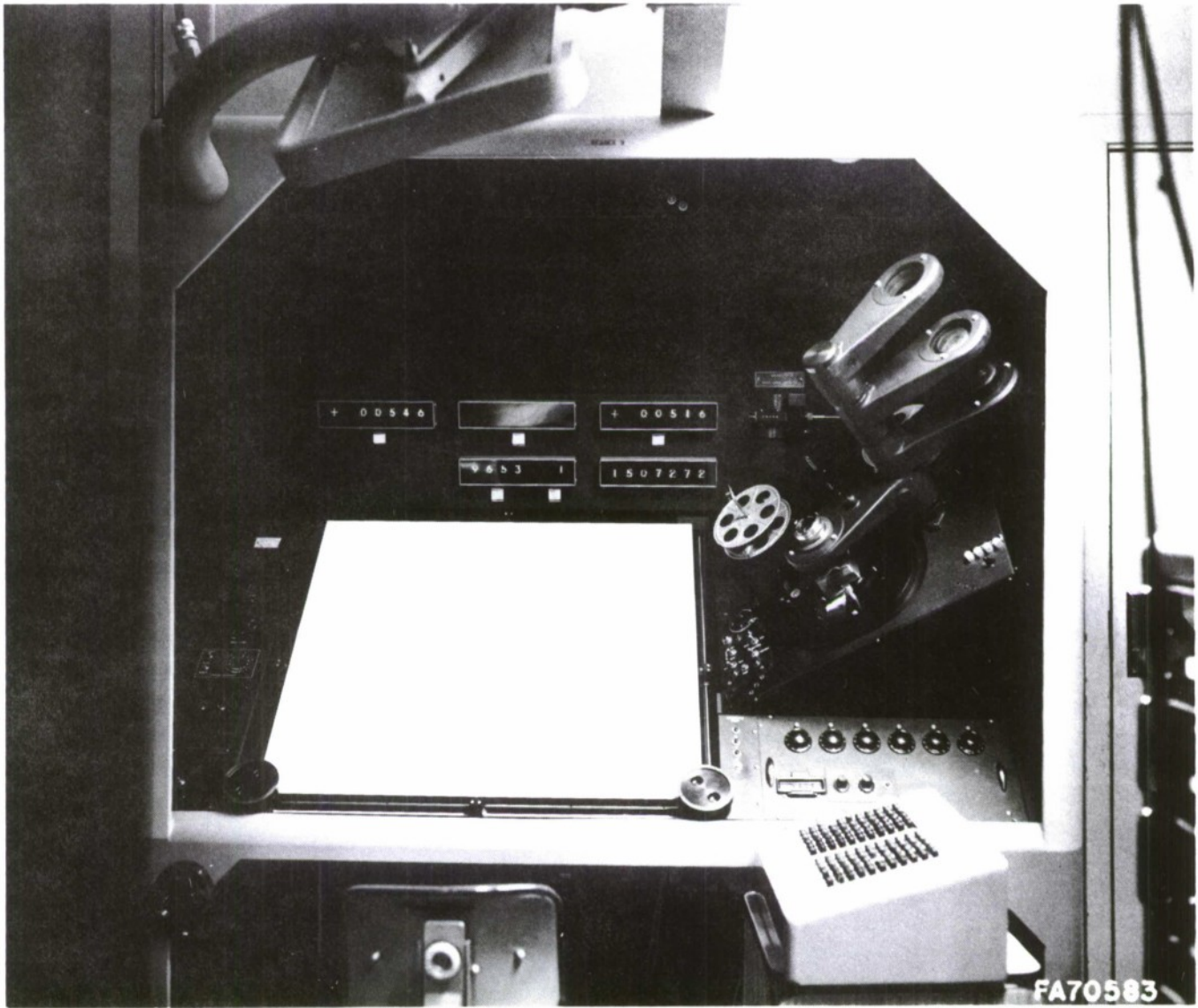


Fig. 8. Film Data Reduction Equipment

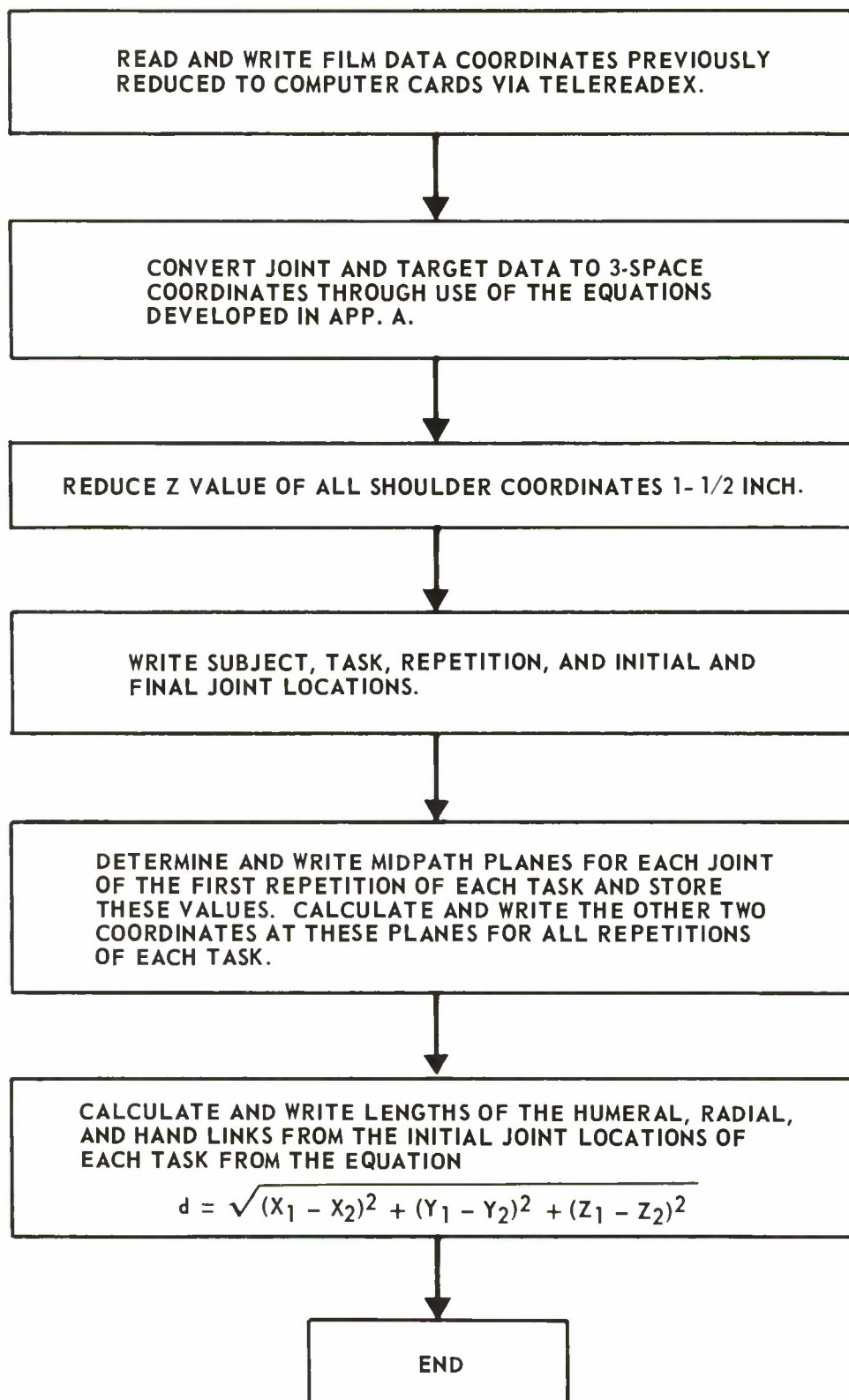


Fig. 9. Abbreviated Flow Diagram of the Computer Program for Obtaining the Right-Arm Movement Data

3.2.1.1 Right-Arm Movement Data Reduction (cont.)

After converting the film data to three-space coordinates, the program determined the link lengths of the humeral, radial and hand links based on the initial location of each subject's shoulder, elbow, wrist, and hand joints. The distances were calculated using the equation:

$$d = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2} \quad \text{EQ (1)}$$

d = Distance

X_1, Y_1, Z_1 = Spatial coordinates of a joint

X_2, Y_2, Z_2 = Spatial coordinates of a joint distal to X_1, Y_1, Z_1

As described in Appendix B, certain trajectory points of the joints were to be compared with the man-model. The largest discrepancies between the man-model and a human were assumed to occur at planes midway in the path of each joint. These planes were established during the first repetition of each task by determining the axis of maximum displacement of the hand. These planes are normal to the axis of maximum displacement at the midpoint of each joint. That is, if the principal motion to accomplish the task was in the Y-direction, then the Y-coordinate of the midpath of each joint was stored. This then establishes a plane (Y = constant) for each joint for referencing all subsequent repetitions. This plane is subsequently referred to as the "midpath plane". Figure 10 illustrates this procedure for the wrist joint only. Each succeeding

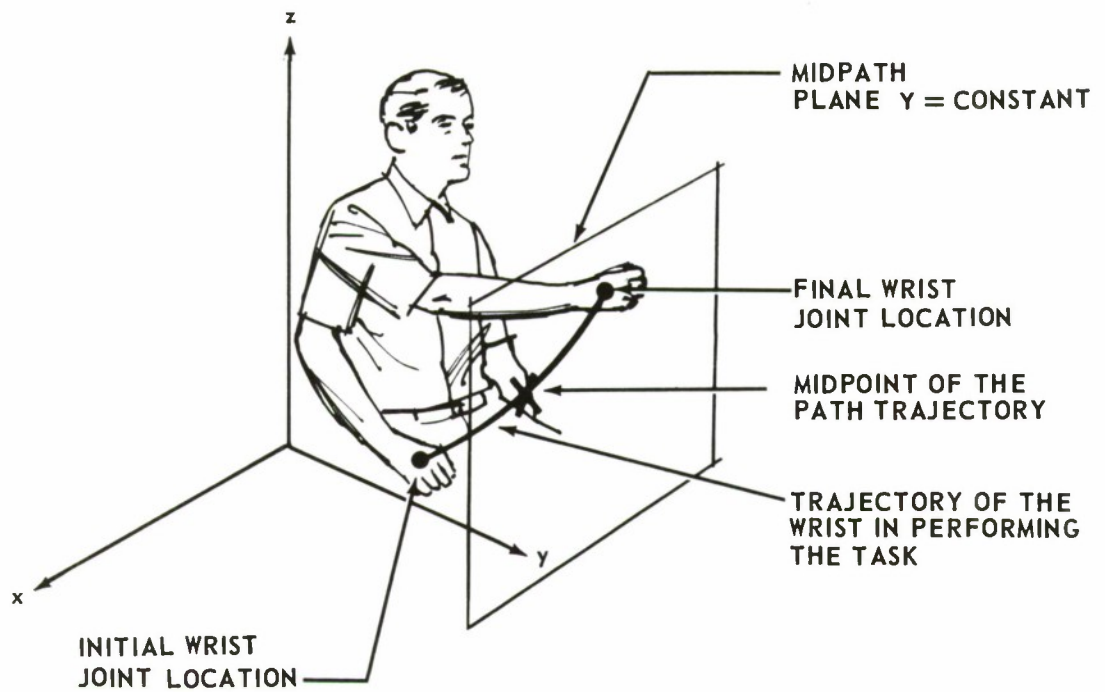


Fig. 10. Midpath Plane for the Wrist Joint

3.2.1.1 Right-Arm Movement Data Reduction (cont.)

repetition of the same task provided additional (X, Z) values as each joint passed through its defined midpath plane.

The result was a scatter of points for each joint from which the statistical comparison with the synthesized joint locations at the same midpath planes could be performed. To further illustrate this scatter of points, Figure 11 is provided. This figure is for one joint and assumes that the principal motion occurred in the Y-direction. The scatter of points is the variation occasioned by a single subject repeatedly performing the same task.

3.2.1.2 Statistical Comparisons

The statistical design given in Appendix B points out that if high correlation (greater than 0.95) occurs between the midpath coordinates of the various joints the effectiveness of the statistical analysis would be reduced. Therefore, after obtaining the midpath data of the general right arm movements and the typical pilot movements, an analysis to determine the amount of correlation was performed.

A computer program was developed to perform the statistical comparison of the midpath joint data of the subjects and that synthesized by the man-model based on the methods described in Appendix B. An abbreviated flow chart of this program is given in Figure 12. As is indicated in

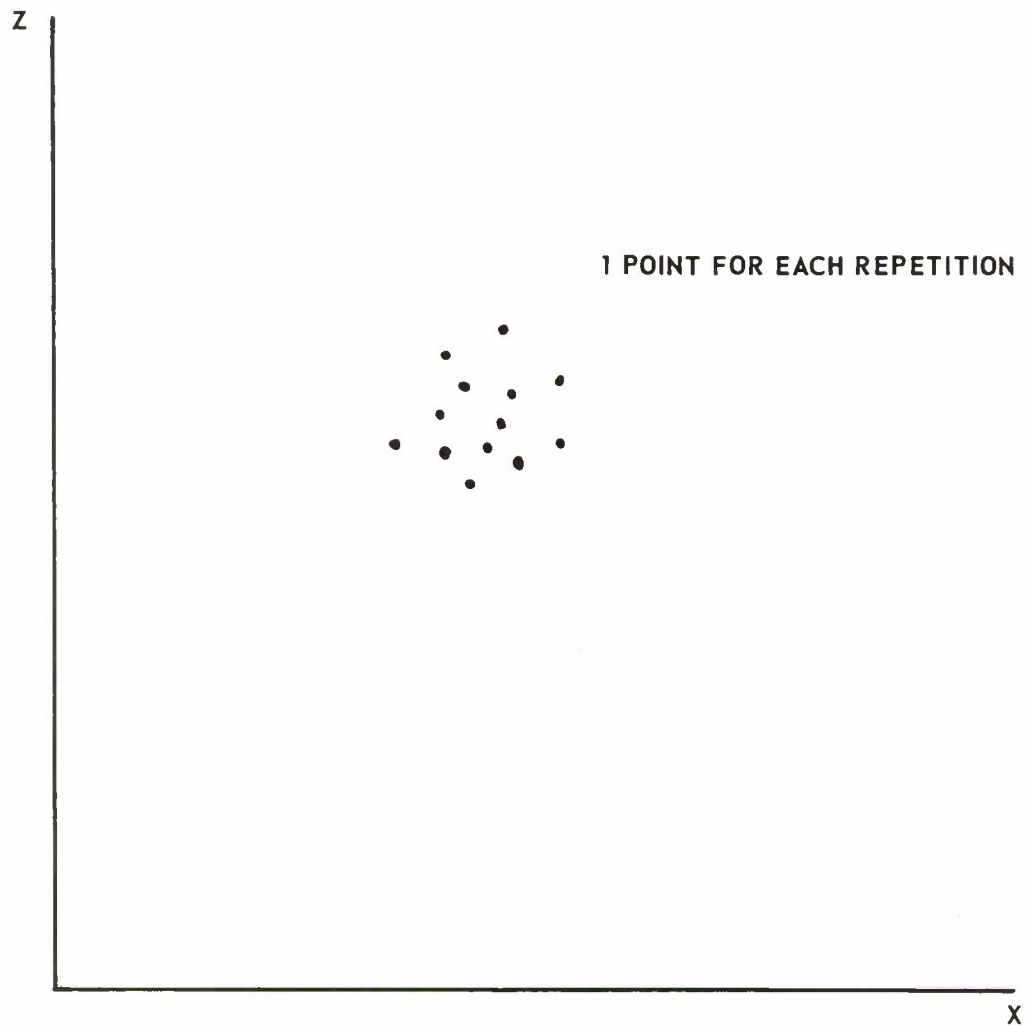


Fig. 11. Example of the Scatter of Points as a Joint Repeatedly Passes Through its Midpath Plane

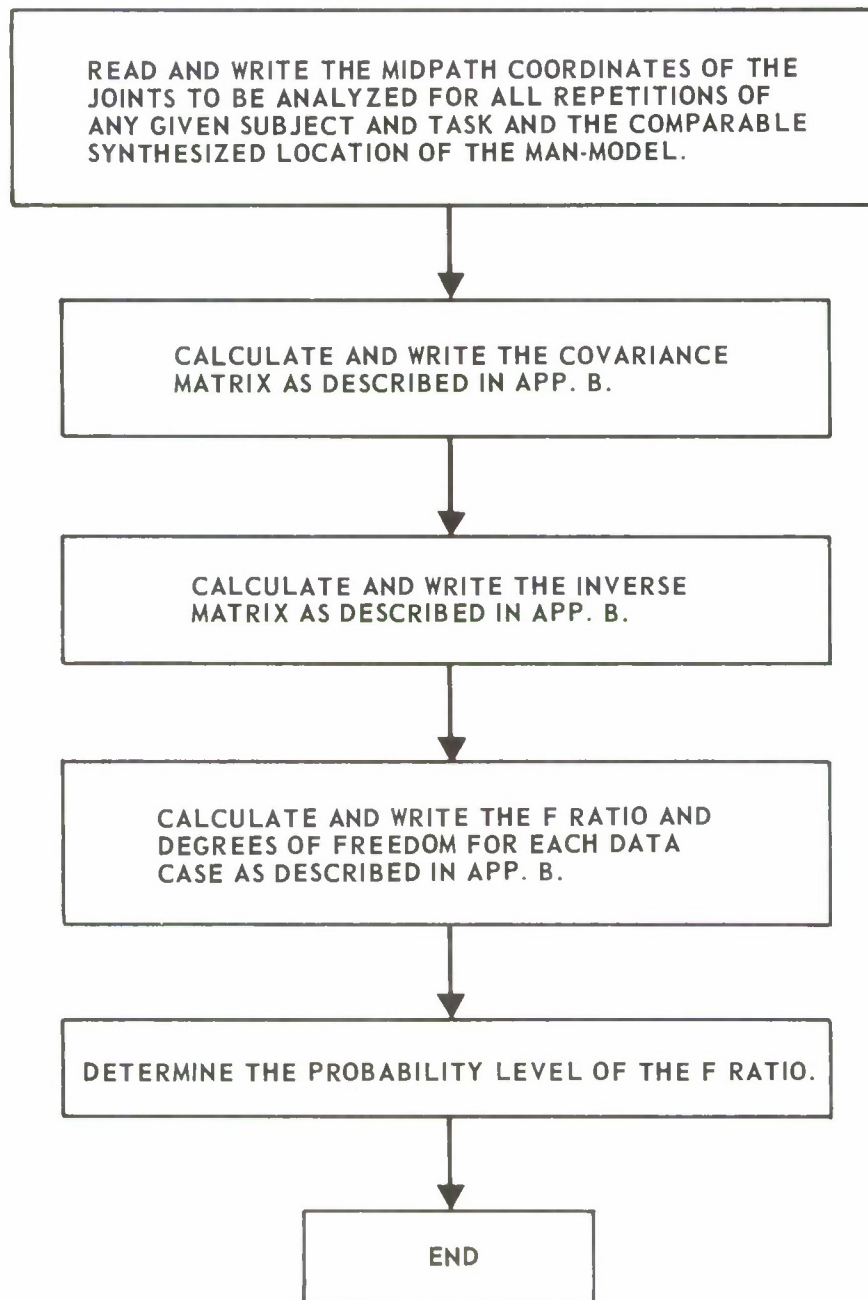


Fig. 12. Abbreviated Flow Diagram of the Computer Program for the Statistical Comparisons

3.2.1.2 Statistical Comparisons

Appendix B, the number of joints compared in the statistical analyses can be varied. By testing different combinations of joints, it was found that useful modifications to the man-model could be more readily identified. The various combinations examined for the one-arm model were: (1) all the joints, (2) all the joints but the shoulder, (3) all the joints except those with high correlation, (4) all the joints except the shoulder and those with high correlation, and (5) the hand only.

3.2.2 Typical Pilot Movements

The second part of the validation was to compare the man-model with typical pilot movements. Each of three subjects repeated a ten-minute mission five times on the Boeing Multimission Flight Simulator. This mission was a training mission which incorporated all of the degraded mode tasks of longer missions but eliminated the intermediate travel. The simulator was programmed to undergo six separate failures during the ten-minute flight. These were: (1) Transfer fuel, (2) Hydraulic system failure, (3) Anti-ice, (4) Right-hand generator failure, (5) Engine overheat and (6) Jettison fuel tanks. From these failures, those movements which appeared to be the most complex were chosen for comparison to the man-model.

Three 16mm motion picture cameras were mounted with the principal axes of the lenses perpendicular to each other. The axes intersected at the

3.2.2 Typical Pilot Movements (cont.)

top of the spine when the subject was seated "at rest". One camera was mounted overhead approximately 14-1/2 feet from the intersection of the principal axes, and the other two were positioned to the left and right sides of the subject to obtain both right and left arm movements. The two side cameras were approximately 11-1/2 feet from the intersection of the principal axes.

Contrasting colored tape was wrapped around the estimated joint centers of the hand, wrist, and elbow. For the shoulder, a strip of tape was laid on the skin surface from the middle of the clavicle down over the shoulder to the middle of the upper arm. This strip of tape was crossed with two perpendicular pieces of tape - one on top of the shoulder joint center as seen in the top view and the other over the joint center as viewed from the side. Figures 13 and 14 show a subject seated in the simulator with the tape at the joint centers. During the actual validation filming the tape was applied directly to the skin rather than over clothing as shown in the above figures. The use of tape as opposed to flashing lights at the joint centers yielded a closer approximation of actual joint center movements.

Three synchronized sweep second hand timers with an accuracy of 0.01 second were positioned within the photo area of each camera. With a known film rate (24 frames per second) and time information, the views could be synchronized and simultaneity of the same joint center in two different views could be guaranteed.

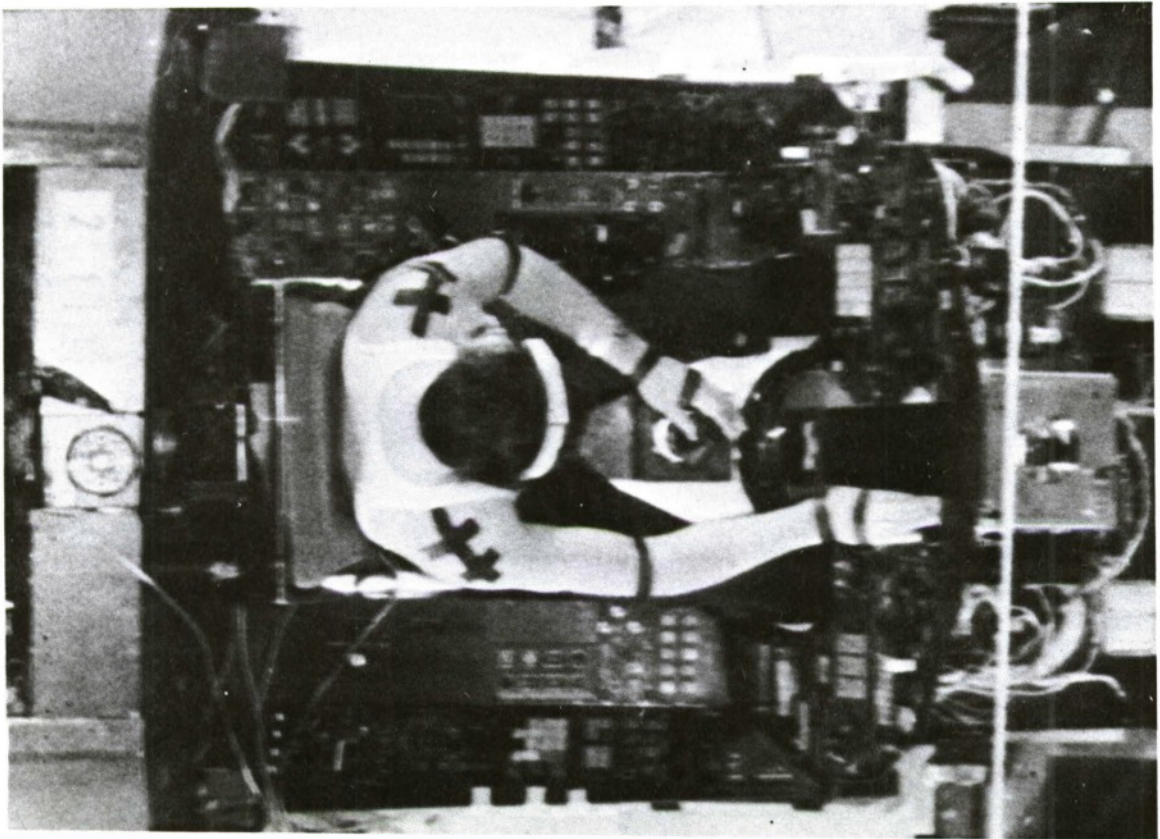


Fig. 13. Top View of a Subject "Flying" The Boeing Multimission Flight Simulator

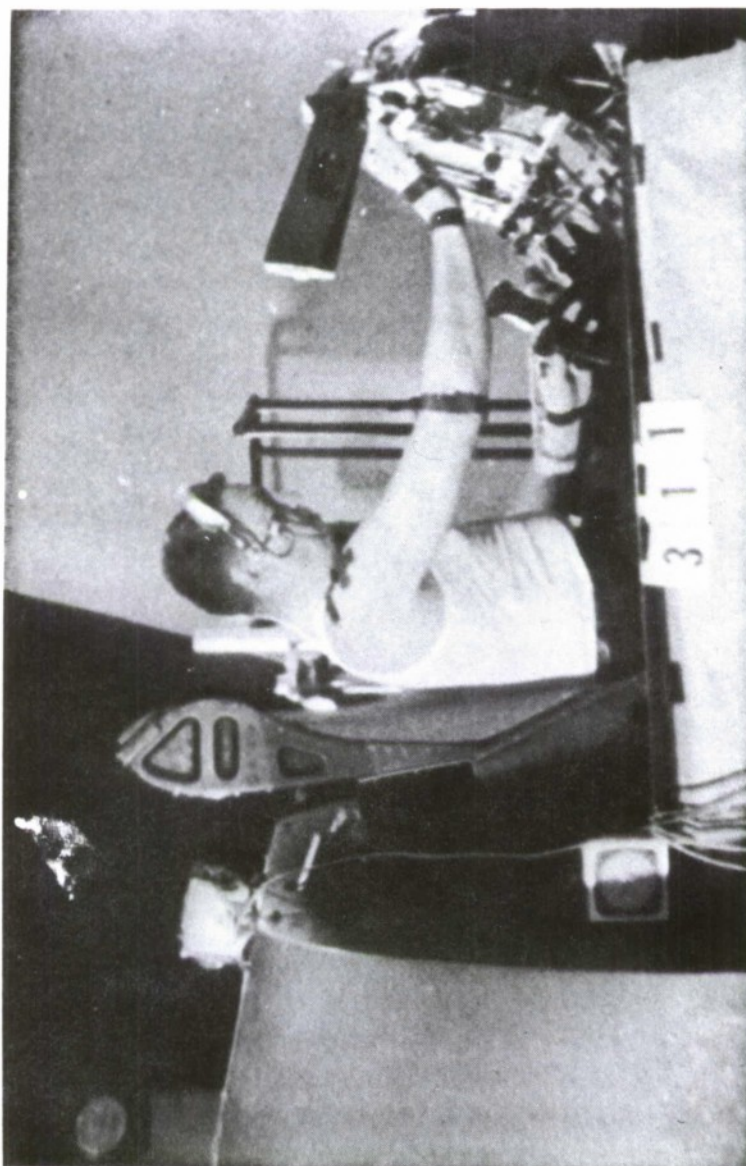


Fig. 14. Side View of a Subject "Flying" The Boeing Multimission Flight Simulator

3.2.2 Typical Pilot Movements (cont.)

The tasks performed in the simulator were of a multiple nature since both hands were involved. Because the man-model receives instructions to move to only one hand per task, it was necessary to break the simulator tasks into subtasks, each containing a movement of a single hand to a new control location. For example, to rectify an icing failure, the left hand moves from the throttles to the control stick; the right hand moves from the control stick to the master caution button, to the anti-ice switch for failure correction and back to the control stick, and then the left hand returns to the throttle. Hence, this task has five subtasks (tasks for the man-model). Figures 15 and 16 show the pilot's station of the multimission flight simulator on which the location of the aforementioned items are circled.

3.2.2.1 Typical Pilot Movement Data Reduction

The film data were reduced to computer cards in the same manner as previously described for the general right-arm movements. A computer program was again developed to convert the data to true three-space coordinates. The program determined the starting point of each subtask. Figure 17 is an abbreviated flow diagram of the computer program used to obtain typical pilot movement data. The sections of the program to reduce the film data to three-space joint locations, the determination of midpath planes of the joint excursions, and the calculation of link lengths for each subject and subtask were similar to those described for the general right arm movements.

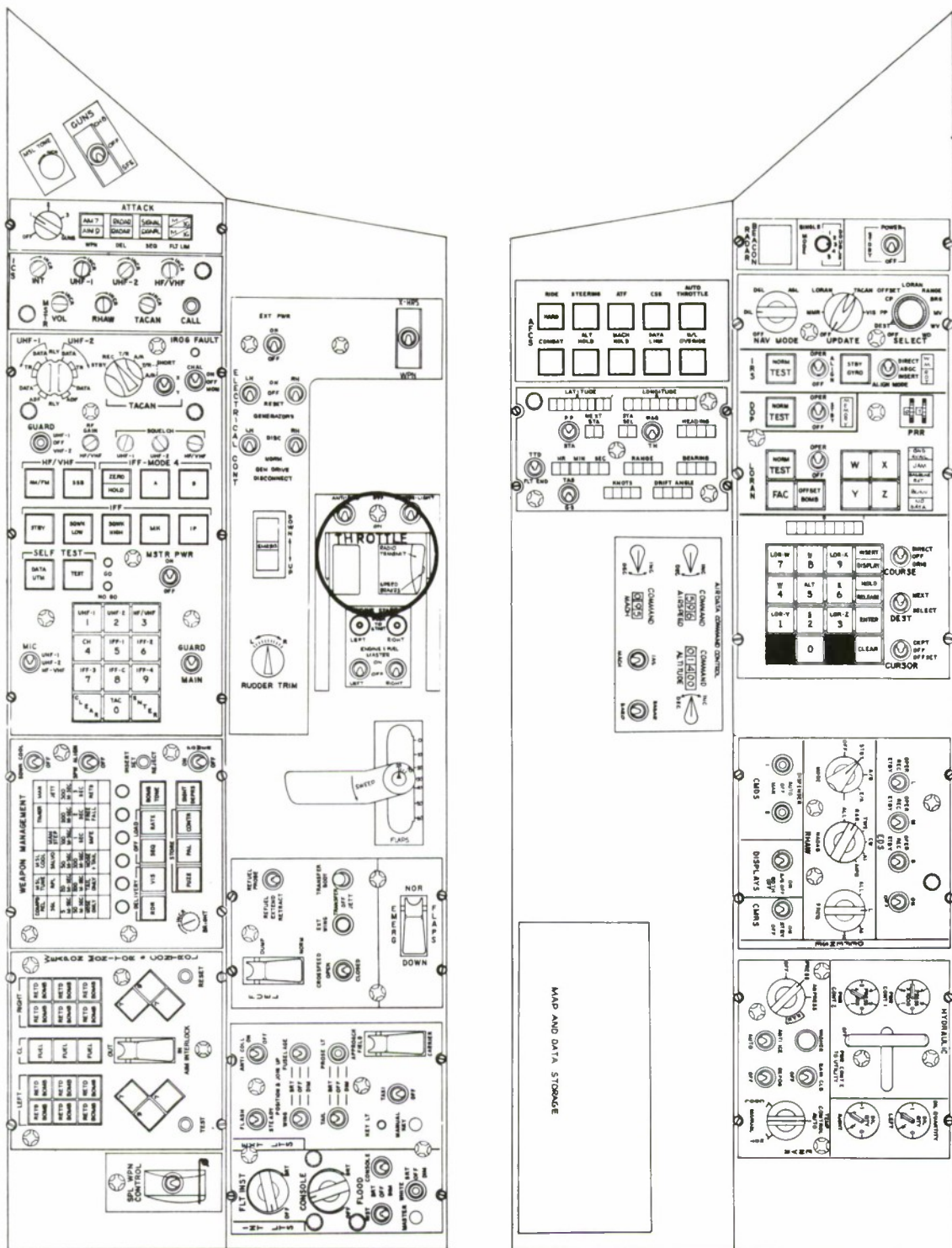


Fig. 16. Side Control Panels of the Boeing Multimission Flight Simulator

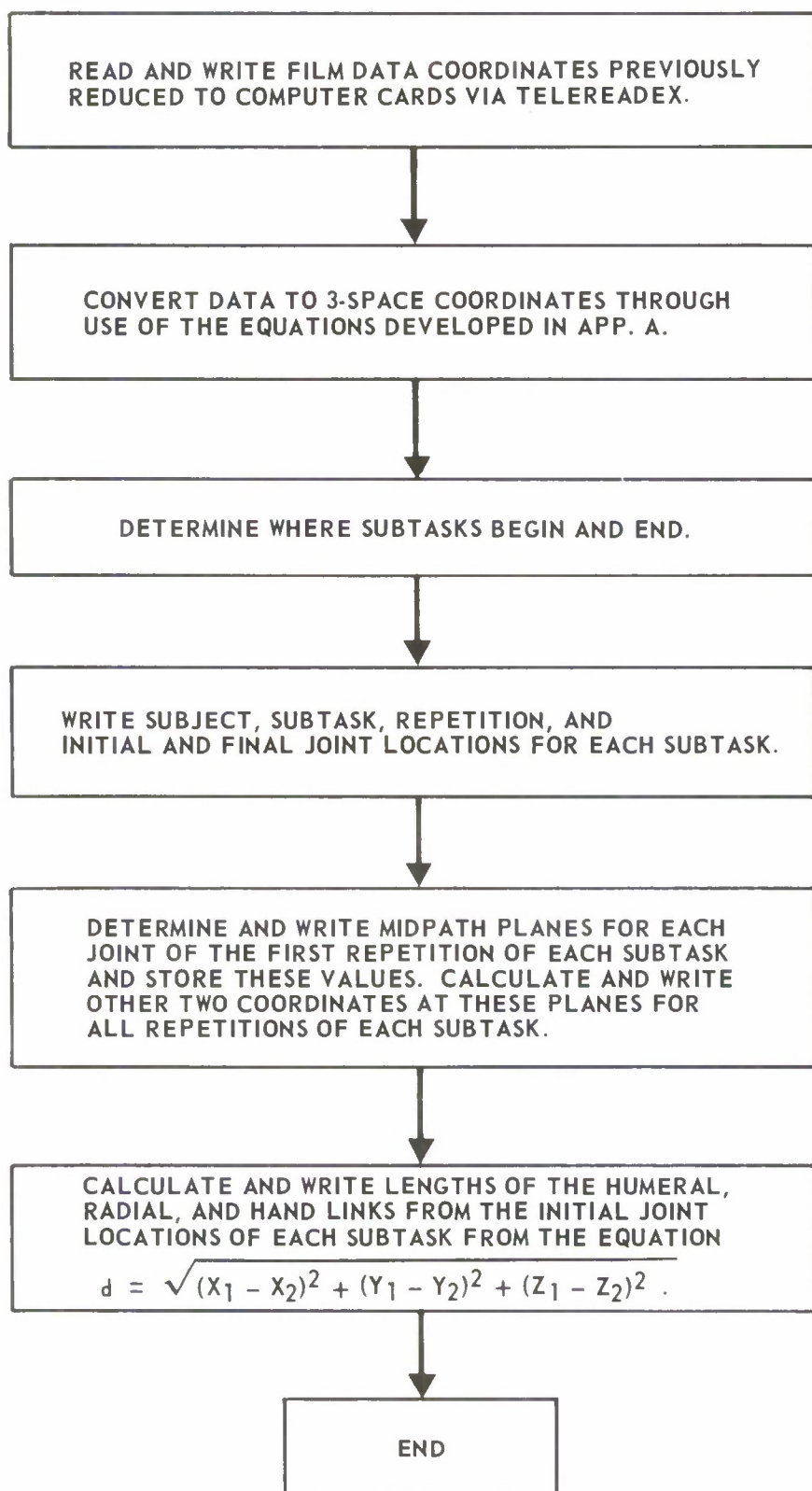


Fig. 17. Abbreviated Flow Diagram of the Computer Program for Obtaining the Typical Pilot Movement Data

3.2.2.2 Statistical Comparisons

The computer program used to perform the statistical comparison on the general right arm movements was also used to compare the man-model with the typical pilot movement data. The combinations of joints statistically compared were:(1) the hand and elbow joints, and (2) the hand only.

3.2.3 Man-Model

3.2.3.1 General

The development of a computerized mathematical man-model has been and will continue to be the key to the provision of a computerized geometry evaluation tool. The man-model which has received the greatest effort in this phase of the program and the model on which the statistical validation was performed is an optimization model. The optimization model synthesizes joint locations and body segment orientations during a task. The man-model begins in a specified position and moves the hand in a straight line from the initial to the final location for that task. The optimization of the man-model is based on the assumption that human motions can be represented by a mathematical function. This function, called an objective function, is an expression of angular deviation from a prespecified "preferred" joint angle. The optimization model minimizes this objective function while simultaneously satisfying link length and terminal joint location and orientation constraints. That is, it minimizes the amount of angular

3.2.3.1 General (cont.)

displacement of each of the interior joints while still reaching the desired control. In doing this, it keeps the body segments as close as possible to the predefined "preferred" orientations.

Each joint is given a weighting factor, called a penalty function, so that some joints are more likely to move than others. For example, the penalty against movement is much smaller on the wrist, elbow and shoulder joints than for the thoracic joint. This appears reasonable since humans prefer to move only their arms to perform a task if torso movement is not required. A detailed description of the man-model is available in Volume IV of this final report, (D162-10127-1).

As was indicated previously, the development of the man-model was conducted in stages as illustrated in Figure 18. Stage 1 provided for unconstrained movement of only one arm with a rigid spine link. Stage 2 placed angular constraints on the movable joints of the model, and Stage 3 added constrained movement of the spine. In Stage 4, links for the other arm, head and neck were added and all angular constraints were removed. This provided unconstrained movement of the entire man above the base of the spine. Stage 5 which is presently being developed, places angular constraints on all the joints.

The validation of the man-model was designed to parallel the stages of the man-model development beginning with Stage 3 and continuing with

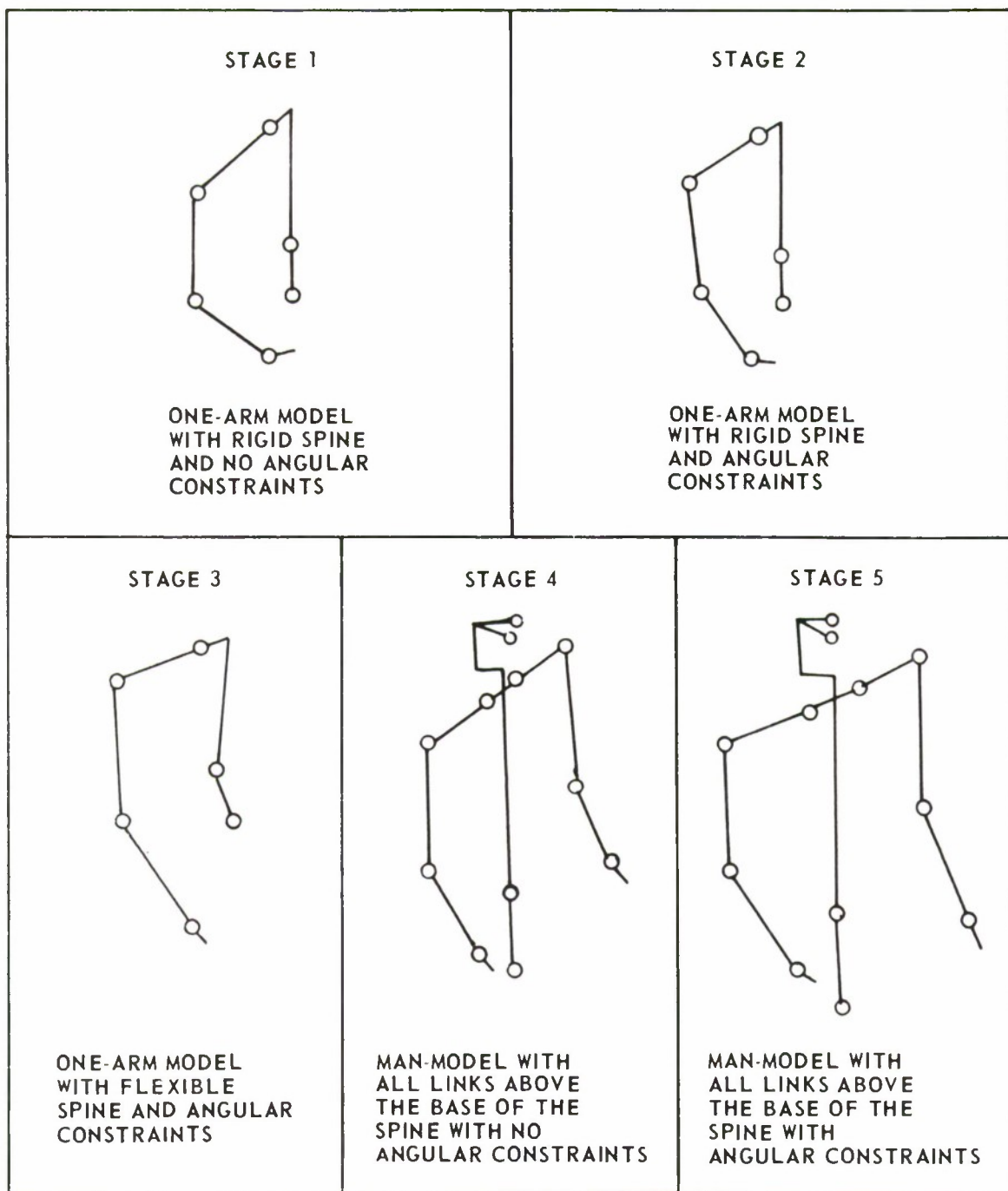


Fig. 18. Development Stages of the Man-Model

3.2.3.1 General (cont.)

Stages 4 and 5. In this way, the validation provided feedback to assist and improve the man-model. The general right arm movement data were used to validate and refine the one-arm/spine man-model developed by the end of Stage 3 and the typical pilot movement data were used in Stages 4 and 5.

Part of the data, methods and concepts of the statistical validation were applicable to all stages of development. To perform any meaningful validation and analysis of man-model movement compared to human movement, it was imperative that:

1. The man-model perform the same tasks as the subjects.
2. The man-model have the same link lengths as that for the subject it was being compared with.
3. The man-model perform the task in a coordinate system having a common origin with the subject.
4. The man-model begin the task with its initial joint locations the same as those of the subject.

3.2.3.2 One-Arm/Spine Model

For the validation of the one-arm/spine man-model developed in Stage 3 (henceforth called the one-arm model), input data from the general right arm movements combined with certain assumptions were used. Typical

3.2.3.2 One-Arm/Spine Model (cont.)

subject data for one task are given in Appendix C and are used for illustrative purposes. The methods described for this data case were repeated for each subject and task.

To provide the same link lengths for the one-arm model as the subject being compared, the average initial joint locations were used in Equation 1. For example, the humeral link (L_H) for the man-model would be determined from the typical subject data as follows:

$$(1) \quad L_H = \sqrt{(14.22 - 9.43)^2 + (4.20 - 2.85)^2 + (10.82 - 20.56)^2}$$
$$= 10.94 \text{ inches}$$

The radial and hand links would be calculated in the same manner. The remaining link lengths (clavicular, interclavicular, thoracic, and lumbar) and orientations are unavailable from the subject data and therefore, were derived. This non-availability of link lengths is not a function of the experimental design but of the fact that outside body landmarks are not precise enough to determine the terminal locations of these links. More accurate data on these link lengths based on cadaver measurements is available from Dempster (1) and the percentage height of the individual subject compared to the 1950 USAF Anthropometric survey (4). These link data have been collated in Reference 5 and are presented in Table 2. For example, if the subject's standing height is the same as the

Table 2. Link Dimensions for Baseline Man-Model

No.	Link	σ		1st Percentile		50th Percentile		99th Percentile	
		cm	in	cm	in	cm	in	cm	in
1	Stature	6.19	2.44	161.3	63.5	175.6	69.1	190.3	74.9
2	Eye Height, Standing	6.04	2.38	150.3	59.2	164.4	64.7	178.5	70.3
3	Eye Height, Sitting	3.22	1.27	72.4	28.5	80.0	31.5	87.3	34.4
4	Interpupillary	0.36	0.14	5.5	2.2	6.3	2.5	7.2	2.8
5	Eyeball to Head	0.00	0.00	14.0	5.5	14.0	5.5	14.0	5.5
6	Head	0.23	0.09	14.7	5.8	15.2	6.0	15.7	6.2
7	Neck (Horizontal)	0.00	0.00	3.8	1.5	3.8	1.5	3.8	1.5
8	Neck (Vertical)	0.15	0.06	10.2	4.0	10.4	4.1	10.9	4.3
9	Inter-Clavicular	0.00	0.00	5.1	2.0	5.1	2.0	5.1	2.0
10	Clavicular*	0.64	0.25	12.6	6.0	14.1	6.6	15.6	7.1
11	Humeral	1.03	0.41	27.8	10.9	30.2	11.9	32.6	12.8
12	Radial	0.85	0.34	25.2	9.9	27.2	10.7	29.2	11.5
13	Hand (Wrist to Hand C.G.)	0.21	0.08	6.5	2.6	7.0	2.8	7.5	3.0
14	Hand (Extended)	0.86	0.34	17.0	6.7	19.0	7.5	21.0	8.3
15	Thoracic	0.94	0.37	29.7	11.7	31.8	12.5	34.0	13.4
16	Lumbar	0.32	0.13	4.0	1.6	4.6	1.8	5.3	2.1
17	Pelvic (Vertical)	0.62	0.25	7.9	3.1	9.3	3.7	10.7	4.2
18	Pelvic (Horizontal)	0.97	0.38	15.5	6.1	17.1	6.7	20.1	7.9
19	Femoral	1.67	0.66	39.5	15.6	43.4	17.1	47.3	18.6
20	Tibial	1.79	0.71	36.7	14.4	40.9	16.1	45.1	17.8
21	Foot (ankle to Floor)	0.38	0.15	7.7	3.0	8.6	3.4	9.5	3.7

*Shoulder link has zero length for BOEMAN-I; 1" added to clavicular length.

3.2.3.2 One-Arm/Spine Model (cont.)

50th percentile USAF height (69.1 in.), the subject is then assumed to have a lumbar link length of 1.8 in., a thoracic length of 12.5 in., a clavicular length of 6.6 in., and an interclavicular length of 1.0 in. (distance from the interclavicular joint to the top of the spine). The clavicular and interclavicular lengths are assumed to lie in a straight line in the negative X direction from the right shoulder, with the Y and Z coordinates the same as the shoulder coordinates. In the typical data case, the initial coordinates of the shoulder joint of the subject are (9.43, 2.85, 20.56). The top of the spine would then have coordinates of (1.83, 2.85, 20.56). (See Figure 19)

The thoracic and lumbar links (the spine) are assumed to lie in a straight line in an $X = 0$ plane and are displaced forward to form a 12° angle with a vertical line. This angle was based on measurements of the shoulder joint locations of seated subjects and the known seat-back angle. Thus the base of the spine (lumbar joint) would have coordinates (1.83, 5.82, 6.56) as shown in Figure 19.

The same initial joint locations of the one-arm model and the subject and task to which it is being compared are obtained by specifying that the one-arm model start at the average initial joint locations of the subject. Hence, the initial position of the man-model, for the stated example, is also shown in Figure 19. The man-model uses these initial joint locations and synthesizes the joint paths to place the hand in the terminal position.

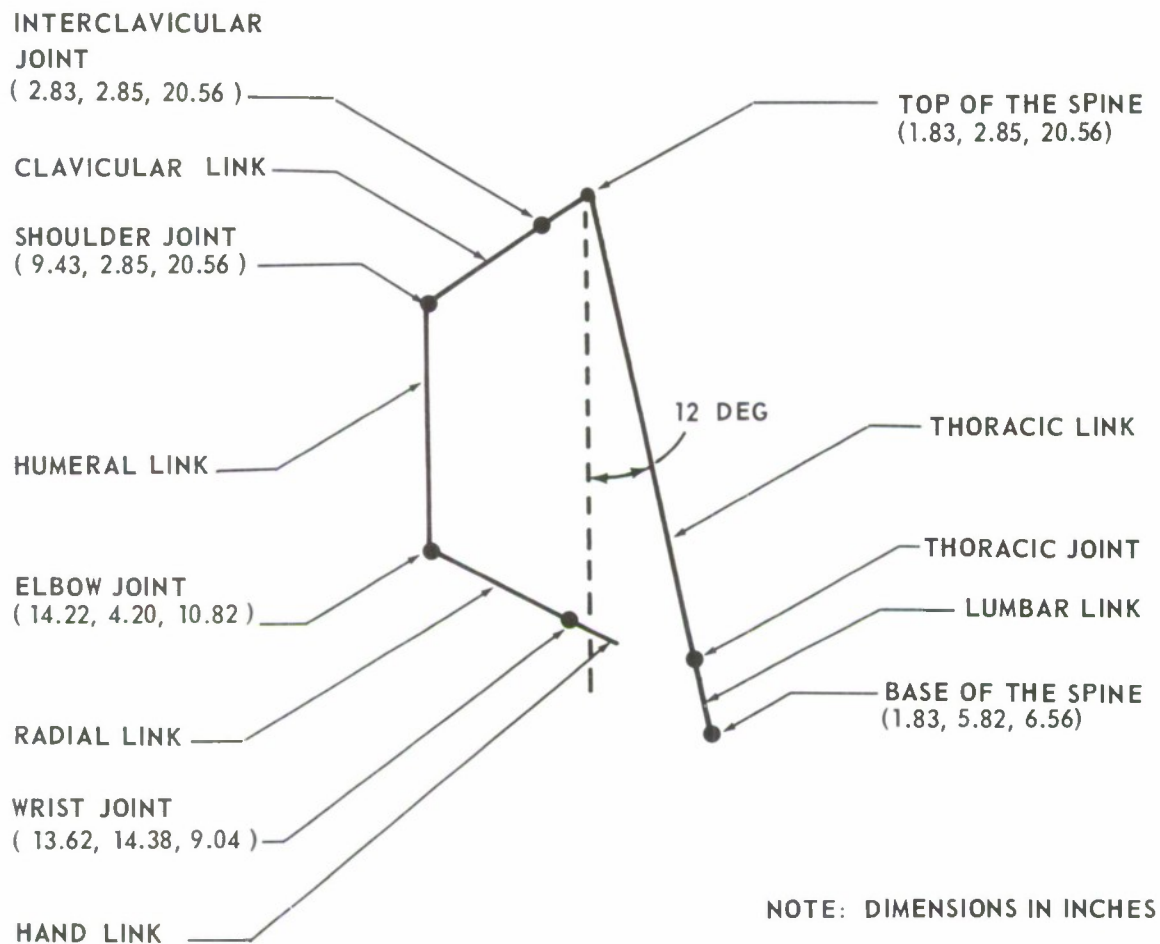


Fig. 19. Initial Position of the One-Arm Model for the Typical Data Case

3.2.3.2 One-Arm/Spine Model (cont.)

The remaining requirement that the man-model perform the same task as the subject is attained by specifying the final average hand position of the subject as the final constraint. Thus, in the typical data case, the model is reaching for (7.98, 25.70, 14.91).

For statistical comparison synthesized joint locations must be obtained at the midpath joint planes of the subjects. Thus, in performing the task of the typical data case the midpath planes are $Y = 3.7$ for the shoulder, $Y = 9.5$ for the elbow, $Y = 19.1$ for the wrist, and $Y = 21.2$ for the hand. As the one-arm model's joints pass through their respective planes, the other two coordinates (X and Z) are obtained at these planes. These are subsequently used for statistical comparison, and to indicate modifications to the man-model.

The modifications to the man-model, based on the results of the statistical analyses, were made by changing the penalty (weighting) functions of the joint angles, and the "perferred" orientations of the body segments. Thus a trial and error (iterative) technique was used to improve the model. When it appeared that a reasonable one-arm model was attained, development of the unconstrained full upper torso model was begun.

3.2.3.3 Full Upper Torso Model

The photographic reduction of the typical pilot movements provided the basis for statistical comparison with Stage 4 of the man-model development

3.2.3.3 Full Upper Torso Model (cont.)

(unconstrained full upper torso). These data will also be used for validation of Stage 5 (angularly constrained full upper torso model).

The validation of the Stage 4 man-model followed many of the procedures and assumptions developed for the one-arm validation. Length of the arm-links were calculated from the initial joint locations. The length of the lumbar and thoracic links, based on the percentile of the subject's stature, were used. The average initial joint locations were used for the starting position of the man-model. This provided common initial joint locations for the subjects and the man-model. The final hand location was specified in order that the same task was performed. The midpath plane for each joint was specified to allow statistical analysis of variation between the subjects and the man-model. The midpath plane of the shoulder, however, was omitted since visual inspection of the reduced data revealed that little, if any, shoulder movement was required for the tasks.

The interclavicular and clavicular links were assumed to lie on a straight line between the left and right initial shoulder joint locations for each subtask. The midpoint of this line is the top of the spine and the interclavicular joints lie one inch in each direction along this line. From the interclavicular joint to the shoulder joint locations are the clavicular links. Any differences between the Y- and Z-coordinates of the two shoulder locations were assumed to have been caused by rotation and bending at the thoracic joint.

3.2.3.3 Full Upper Torso Model (cont.)

It was necessary to arrange the validation data to be compatible with the man-model input requirements. This required definition of the lumbar joint location. The lumbar joint location was arrived at by translating from the shoulder joint locations to the lumbar joint. The thoracic link is assumed to lie on a line making a 90° angle with the interclavicular link and having a minimum Z-value. The lumbar link lies along a line straight down the Z-axis from the thoracic joint to the lumbar joint.

The final joint locations of a subtask become the initial joint locations of the next subtask. However, to have a common basis for performing a subtask, it was required that the man-model have initial joint locations identical to those of average initial joint locations of the subject. Therefore, at the completion of each subtask the man-model was repositioned from the previously synthesized locations to the final average joint locations of the subject. This initialized the man-model in the same starting location as the subjects for statistical comparison of the next subtask. In addition new link lengths are calculated, assumptions about the top and bottom of the spine were again carried out and the man-model was ready to perform the next subtask. This process was continued until the final subtask of the overall task was completed. As was stated, if the man-model has performed the subtask similarly to the subject, these adjustments to acquire the subject's final average joint locations would be minimal. In addition, if the initial and final joint locations from the film data were carefully obtained the changes in link lengths between subtasks would be negligible.

3.2.3.3 Full Upper Torso Model (cont.)

The data from the man-model at the midpath planes of the joints were compared to the human data at these same respective planes for each subject and subtask. The statistical analyses, in addition to examining the effectiveness of the man-model, provided feedback for improvements. These improvements were again accomplished by modifying the weighting factors of the penalty function and the "preferred" body segment orientations.

4.0 RESULTS

Typical results of the midpath joint comparisons of the one arm model (Stage 3) with the right arm movement data are presented in Figure 20 and 21, and in Tables 3 and 4. These illustrate four of approximately 70 cases analysed. A visual inspection of the joint locations indicated there is reasonable agreement between the human joint locations and those synthesized by the model. However, of the four cases shown, only the comparison presented in Table 3 is acceptable at the 0.01 probability level. Only three of the 70 cases have this level of acceptability. The magnitude of the differences between the synthesized location and the mean of the subjects joint location (based on 12 repetitions of the same task) was less than two inches in the majority of cases. There were some isolated cases where major differences occurred. This is illustrated by Figure 21 where the subjects hand moved in a high arc toward an overhead control location rather than in a straight line as the man-model is instructed to do. In these cases inspection of computer graphic displays of synthesized movement indicated the terminal joint location of the subjects and the model are similar and the entire movement appeared reasonable.

Midpath joint comparisons of the unconstrained full man-model (Stage 4) with the typical pilot movement data indicated significant differences at the 0.01 Probability level for all cases tested. These differences appear to be small when visually inspected.

• SUBJECT JOINT LOCATIONS

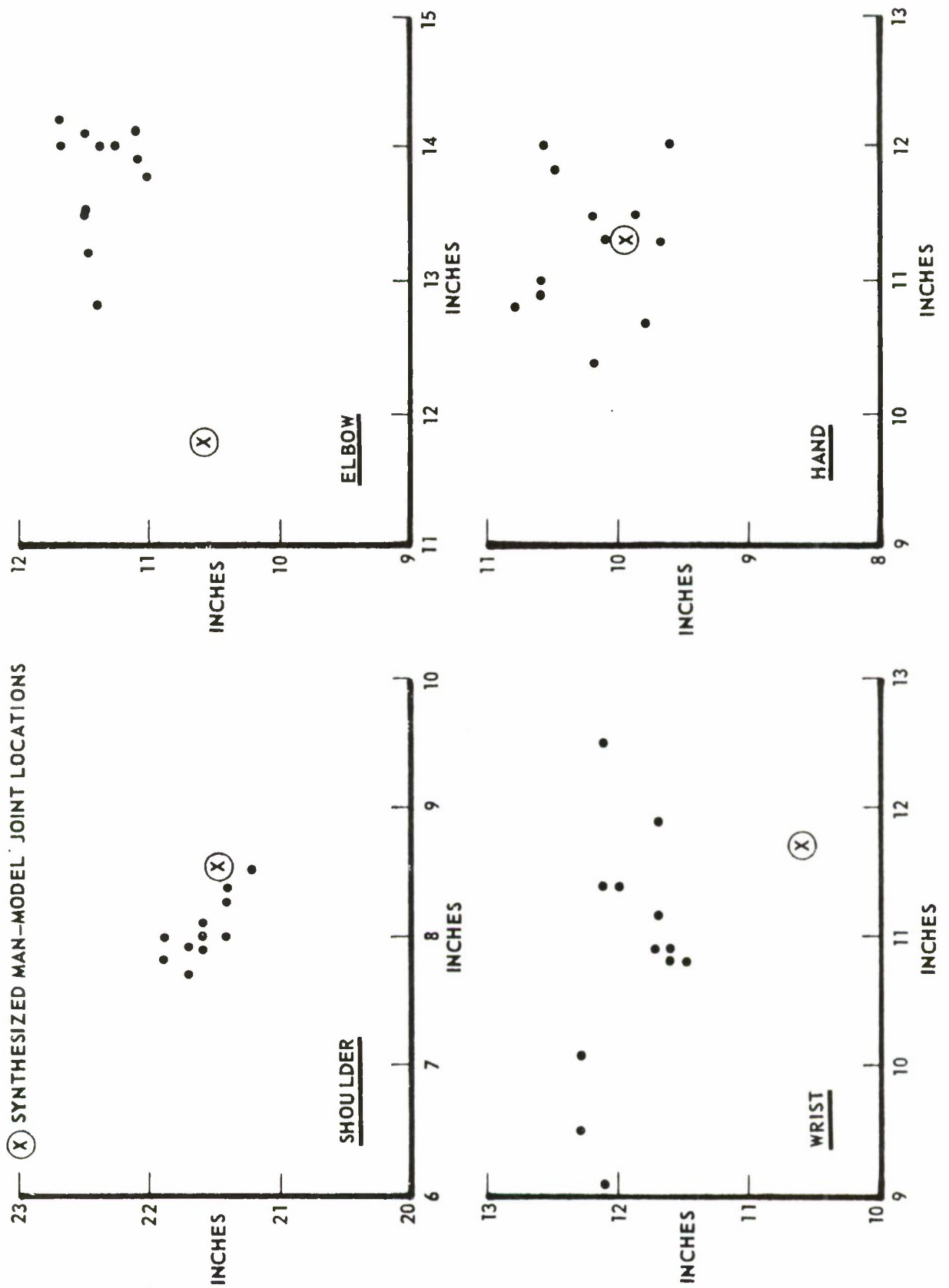


Fig. 20. Comparative Midpath Joint Data for One Task

• SUBJECT JOINT LOCATIONS
 (X) SYNTHESIZED MAN-MODEL JOINT LOCATIONS

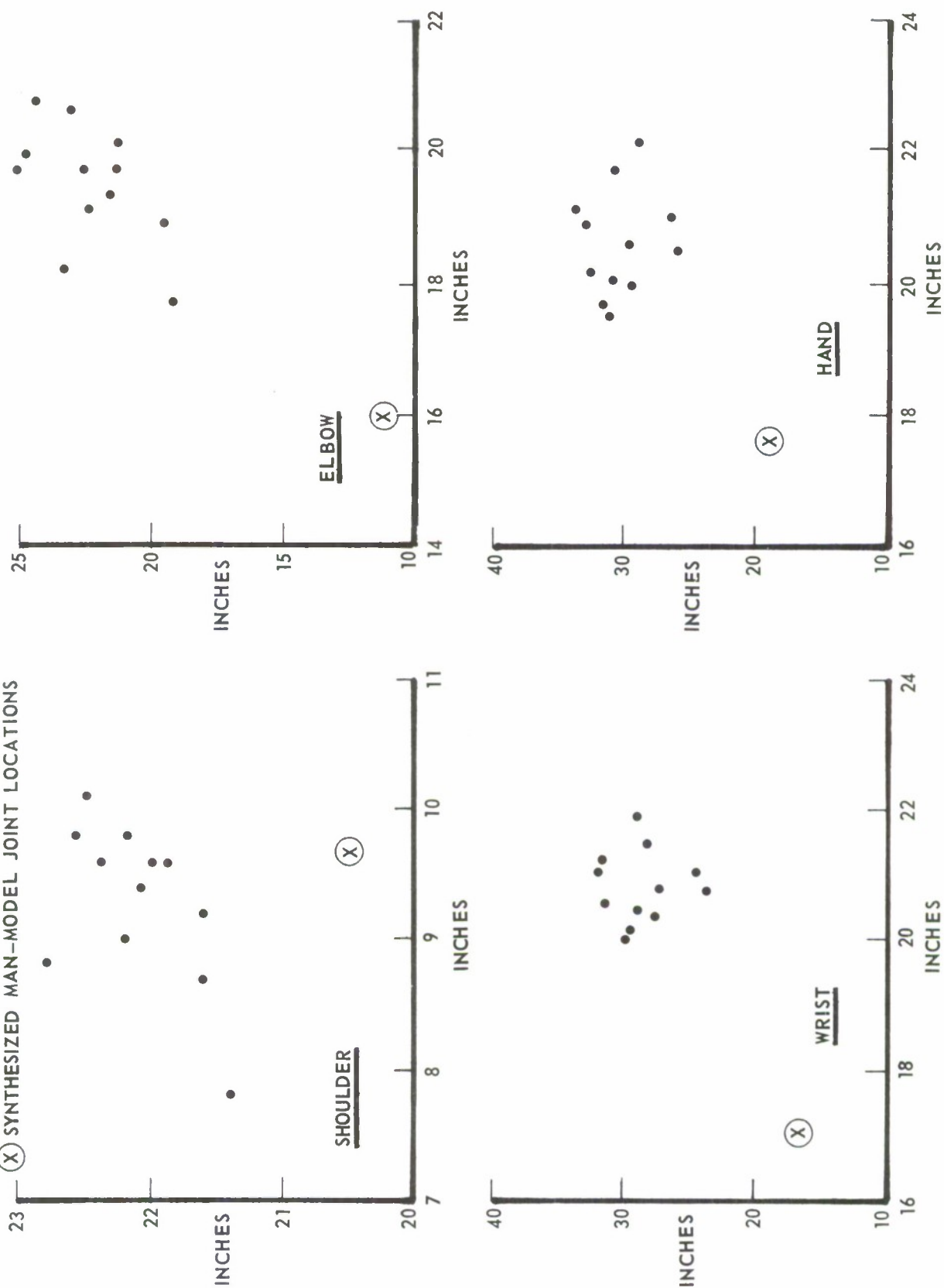


Fig. 21. Comparative Midpath Joint Data for a Task with Large Differences

Table 3. Comparative Joint and Statistical Data for One Task, of a Subject, and the One-Arm Model at the Midpath Plane of the Hand Only

Subject Data for 12 Repetitions		One-Arm Model Synthesized Location	
Hand		Hand	
X	Z	X	Z
10.90	10.60	11.29	9.95
10.80	10.80		
10.40	10.20		
12.00	10.60		
11.30	10.10		
10.70	9.80		
11.30	9.70		
12.00	9.60		
11.50	10.20		
11.00	10.60		
11.50	9.90		
11.80	10.50		
X = 11.28 Z = 10.50			
F = 2.398 (2, 10)		P > .05	

Table 4. Comparative Joint and Statistical Data, for One Task, of a Subject, and the One-Arm Model at the Midpath Planes of all the Joints

Shoulder		Elbow		Wrist		Hand	
X	Z	X	Z	X	Z	X	Z
8.60	20.70	14.00	12.80	11.20	11.50	8.50	11.30
8.80	20.90	13.30	13.00	11.10	11.90	9.40	12.00
7.70	21.40	14.10	10.60	10.50	12.90	7.60	12.90
7.80	21.50	12.50	13.80	11.20	13.20	10.30	13.10
7.70	21.40	13.00	14.00	11.50	13.30	8.10	13.20
7.90	21.20	13.30	13.60	11.90	12.40	10.40	12.30
7.90	21.00	13.00	13.40	12.50	12.90	11.60	12.20
8.20	21.10	12.80	13.40	11.10	12.60	11.80	12.30
8.20	21.10	13.10	13.30	10.70	11.80	10.00	11.90
8.10	21.10	13.30	13.20	11.60	12.60	10.60	12.60
8.30	21.10	13.60	13.30	11.70	12.60	9.40	13.00
8.30	20.90	12.60	13.10	11.30	12.10	10.40	12.20
$\bar{X} = 8.12$	$\bar{Z} = 21.20$	$\bar{X} = 13.21$	$\bar{Z} = 13.11$	$\bar{X} = 11.36$	$\bar{Z} = 12.48$	$\bar{X} = 9.85$	$\bar{Z} = 12.41$
One-Arm Model Synthesized Locations							
9.417	20.84	11.82	12.85	10.61	12.55	10.32	11.30

Subject Data for 12 Repetitions

$$F = 97.02 (8, 4) \quad .01 > P$$

Taking the statistical evidence at face value would indicate that the man-model is not representative of human movement. Before accepting this promise, the following questions require consideration:

- o How closely should the model represent mid-joint (shoulder, elbow, wrist, etc.) movement if the hand does in fact reach the designated control?
- o Is the statistical test too restrictive?
- o Can realistic comparisons be made when the model is statistically compared with only one subject at a time?
- o Are the human movement data sufficiently accurate for adequate comparisons?

These questions are discussed fully in Sections 2.0, Summary and Conclusions and 5.0, Problems and Recommendations. Based on visual inspection of various data displays, the differences in movement paths between the model and humans, in general, appear negligible. The agreement is sufficient to conclude that the model is feasible and warrants further development.

5.0 PROBLEMS AND RECOMMENDATIONS

Several sets of data on human movements were gathered and reduced to guide the development of the man-model. Inspection of reduced data indicated that a portion was not usable due to problems in acquisition or reduction. The types of difficulties encountered and recommendations to correct these problems are listed in the following sections.

5.1 RIGHT ARM MOVEMENTS

The method given in Appendix A for reducing photographic data to spatial coordinates assumes simultaneity between the points read in different views. That is, the joint location read in one view must have occurred simultaneously with the location read in the other view. This is assured only if the joints are stationary. Hence the initial and final joint locations are accurately determined. Difficulties can arise, however, when trying to ensure the simultaneity of intermediate points along the joint paths when recorded by still cameras. As can be seen in Figure 7, the joint movements produce a series of dashed lines. Normally it is possible to determine which dash lines from both views are in correspondence. Hence, if the start and stop points of the corresponding dashed lines in each view are read, simultaneity occurs. Even though care was used to try and guarantee simultaneity, some of the tasks do not yield distinct and/or differentiable light traces in one of the views. For these tasks, simultaneity was not ensured and these data were discarded.

5.1 RIGHT ARM MOVEMENTS (cont.)

If the light trace of only one joint is not distinct, the entire task is made unusable.

The differences illustrated in Figure 22, between actual joint center locations and the location of the flashing lights were considered. The problem proved to be of little consequence since the joint locations internal to the shoulder were obtained by derivation rather than by actual measurement, and all the joint lights with the exception of the shoulder were displaced in the same direction. The rotation angles of the shoulder and elbow joints remained nearly constant during the performance of the majority of the tasks. In general, the task was begun with hand in a "thumbs up" orientation and remained this way until the task was completed with the thumb being placed over the photocell (target). Therefore, the lights over the hand, wrist and elbow were displaced laterally to the right of the right arm. The motions of the lights, therefore, are similar to the motions of the joints but displaced laterally. The actual location of the lights can then be used to describe the joint-center movements. The comparison is made by starting with the man-model's joint centers at the light locations and comparing midpath points to those of the lights.

The shoulder joint light was placed on top and to the right of the shoulder joint. Therefore, to place it in a similar frame of reference as the other three, the calculated value of the shoulder joint was lowered 1-1/2 inches.

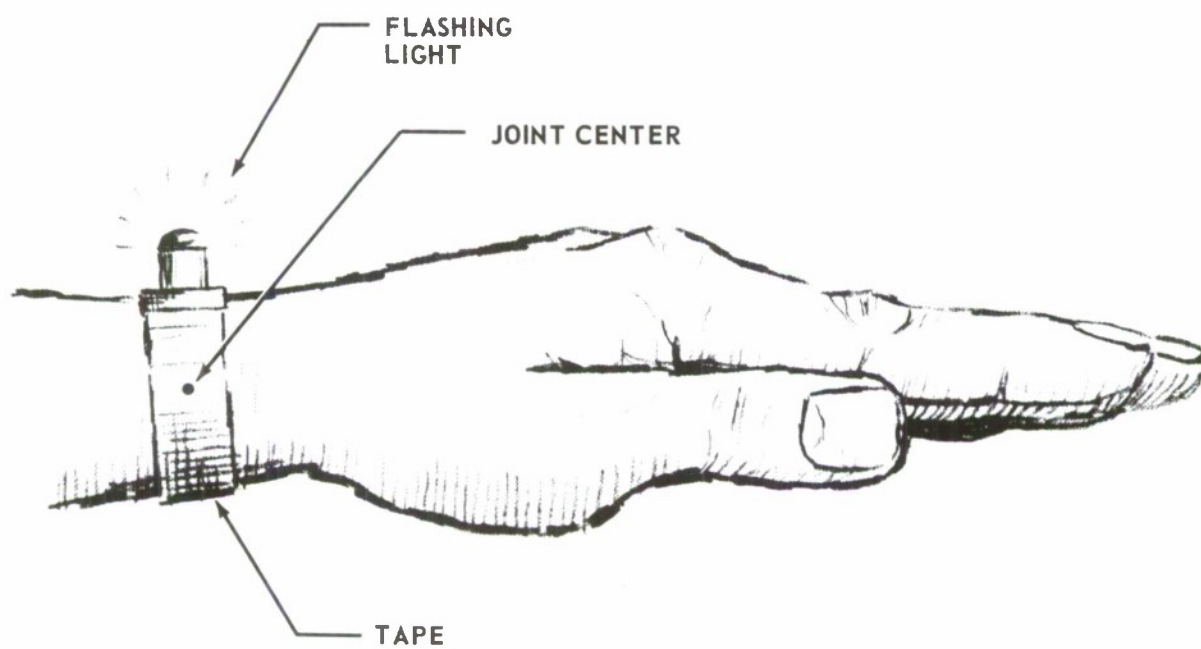


Fig. 22. Differences Between the Actual Wrist Joint Center and the Flashing Light

5.1 RIGHT ARM MOVEMENTS (cont.)

by the computer program. With this adjustment, the discrepancies between joint centers and the lights are of minimal significance.

5.2 TYPICAL PILOT MOVEMENTS

Clocks with sweep-second hands were used in the motion picture filming of the typical pilot movement data to guarantee synchronization between the films from the different views. However, the overhead lights reflected off the face of the clock in the top view and hence the timer hands could not be seen in the film record. To obtain the required simultaneity between the views, since the timer could not be read, a frame counter was used along with visual observation of the film. Small differences in the frame rate of the cameras made the frame count method unreliable, hence only visual observation could be used. From the actual data reduction, it appears that in most instances, this visual observation approach was acceptable.

A more significant problem occurred because of the camera placement. The cameras were positioned such that the intersection of the principal lens axes would be near the top of the spine location. This was done so the subtask motions would occur near the center of the film, thereby reducing image distortion which is likely to occur near the edges of the film frames. However, in doing this, some of the joints passed through the X-Z plane ($Y = 0$). When a joint is read at or near the X-Z plane on

5.2 TYPICAL PILOT MOVEMENTS (cont.)

the Tele-Readex, the Y-value is very small. The method described in Appendix A to obtain spatial coordinates from the film data determines the Y coordinate initially and then determines the X and Z coordinates by multiplying the three-space Y coordinate times the ratios of X/Y and Z/Y respectively. These ratios are still in the coordinate system of the Tele-Readex. If the Y value is relatively small compared with the X and Z values in these ratios, then a small change in the Y value has a large influence on the values of X and Z coordinates. When reducing the film data to computer cards, the joint center position is estimated based on the tape wrapped around the joint and the value of Y can be greatly changed by almost imperceivable variations in the location of the joint center. This change of the Y-value greatly affect the calculated X- and Z-coordinates (200 counts per inch on Tele-Readex). Inspection of the data clearly indicated when such problems occurred and those data were eliminated from the analysis.

5.3 ALTERNATIVE METHODS AND RECOMMENDATIONS

Alternate methods of obtaining joint-center data are available and will be investigated in the next study phase. Other researchers have proposed and partially developed means of determining joint paths of motion using electromechanical devices, such as potentiometers in conjunction with exoskeletons and man-amplifiers (Reference 6 and 7). All other methods determine the paths of a point on the outside of the joint rather than

5.3 ALTERNATIVE METHODS AND RECOMMENDATIONS (Cont.)

the actual joint centers, and a period of time would be required to develop and checkout alternate approaches. In addition, no relationship between the arm-joints and a reference point such as the bottom of the spine exists. The investigations to ~~date~~ do indicate that, with some modification, these methods might be reliable and much more efficient than the tedious and laborious filming techniques. A filming technique using only one camera and reflective mirrors has been reported (Reference 8). In addition computer graphic displays of synthesized man-model movements superimposed on real flight-crew film, illustrated in Figure 23, can be used for comparisons.

Appendix B indicated the statistical design might have inherent limitations. Experience with the analysis during the initial phase indicated the biggest limitation is that it compares the man-model with only one subject at a time. If the data from similarly sized subjects performing the same task were grouped for the statistical comparisons, the data would be more representative of the general population. The situation is analogous to an analysis-of-variance, where within and between sample variations are used in the analysis. Usually the between sample variation is the larger element of the variation. When using only one subject at a time to compare with, as was done during this study phase, this element of the variation could not be considered. Such a grouping of data was not attempted in Phase I of the program since this would assume that the subjects have

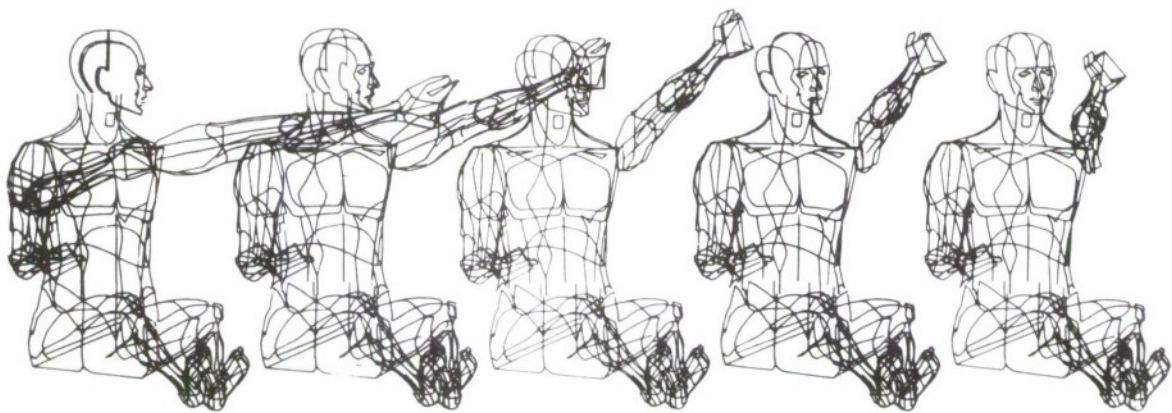
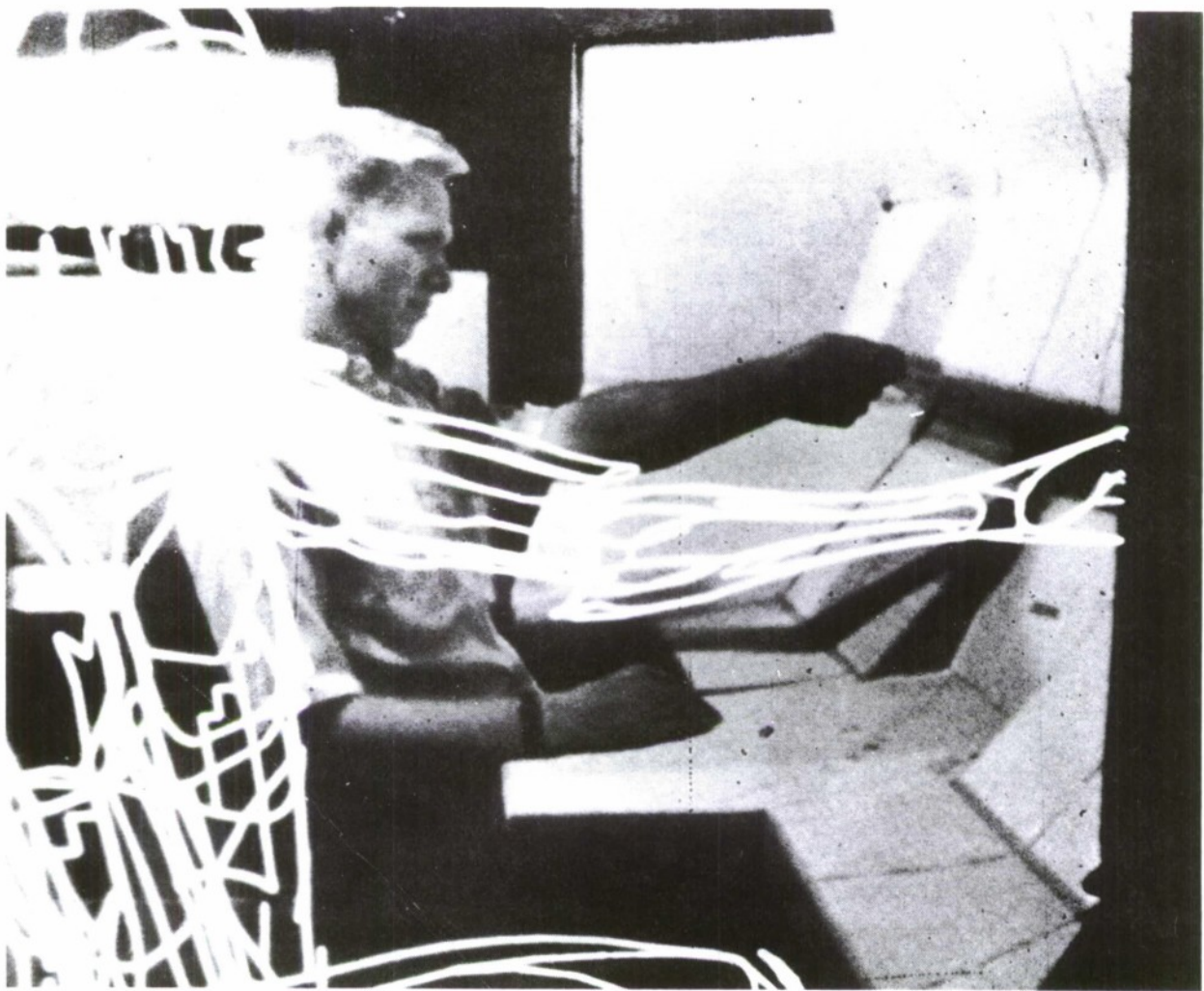


Fig. 23. Superimposed Computer Graphic Display of Man-Model Movements

5.3 ALTERNATIVE METHODS AND RECOMMENDATIONS (Cont.)

identical link lengths, perform the same task, and being the task with their joints in identical initial locations.

If the multi-camera and statistical techniques are used, it is recommended that:

1. High speed movie cameras be used to film the data.
2. The cameras be mounted such that the intersection of their principal axes is behind or in front of the movement to be recorded.
3. Synchronized timers be placed so that they are readable in each view to guarantee simultaneity.
4. The motions to be analyzed be carefully selected so that data reduction time is efficiently utilized.
5. The data of one joint should be completely reduced from the film to data cards before another joint is analyzed. This will place all data from each joint in a single package for efficient handling.
6. Methods be developed so that subjects can be grouped for statistical comparisons with the man-model.
7. Validation criteria be reviewed to establish practical acceptance limits for man-model performance.

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APPENDIX A

DETERMINATION OF 3-SPACE JOINT CENTER LOCATIONS

The spatial location of given joint-centers can be determined from photographs. Two synchronized cameras are mounted such that their principal axes are perpendicular to each other. This provides a common axis such that the other two coordinates can be expressed as a function of the common coordinate. One of the cameras is mounted overhead and the other to the side. The principal axis of the top camera is the Z axis of the coordinate system and the principal axis of the side camera is the X axis of the coordinate system. The origin is defined as the intersection point of these axes. In Figure 24, the common axis, or Y axis, is perpendicular to the page. The definition of the terminology is as follows:

- A = the known distance from the top camera lens to its perpendicular calibration grid.
- B = the known distance from the side camera lens to the above mentioned calibration grid.
- C = the known distance from the side camera to its perpendicular calibration grid.
- L_t = a known distance on the perpendicular calibration grid of the top camera which projects as a distance l_t on the photograph.
- L_s = a known distance on the perpendicular calibration grid of the side camera which projects as a distance l_s on the photograph.

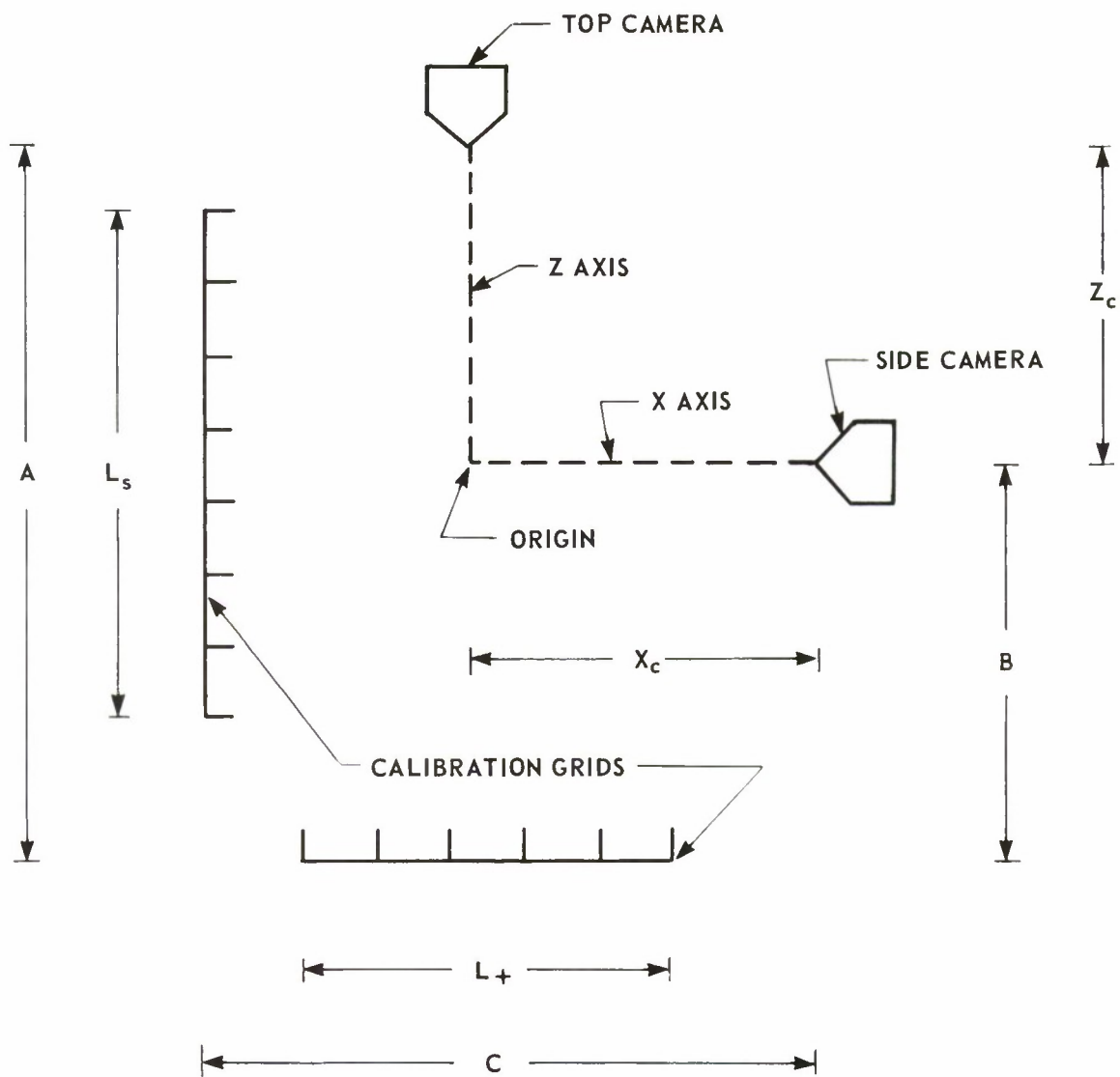


Fig. 24. Experimental Arrangement of the Photographic Technique

APPENDIX A (cont.)

Z_c = the known distance from the top camera to the origin.

X_c = the known distance from the side camera to the origin.

X = the X coordinate of the actual spatial location of
a given point.

Y = the Y coordinate of the actual spatial location
of a given point.

Z = the Z coordinate of the actual spatial location
of a given point.

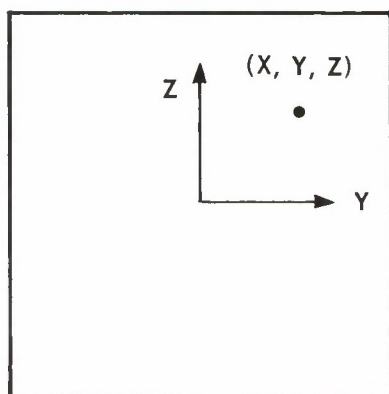
Figure 25 depicts the way a typical joint-center (X,Y,Z) might appear on simultaneous photographs from the side and top cameras. Then X and Z are functions of the common coordinate Y . The 3-space location of the joint-center is established by determining the relationship between photographic locations and spatial locations.

The lengths A , B , C , L_t , L_s , and l_s and the location of the origin have previously been determined. The point (X,Y,Z) is at an unknown distance from the two cameras but it lies some measurable distance on the two photographs from the X and Z axes.

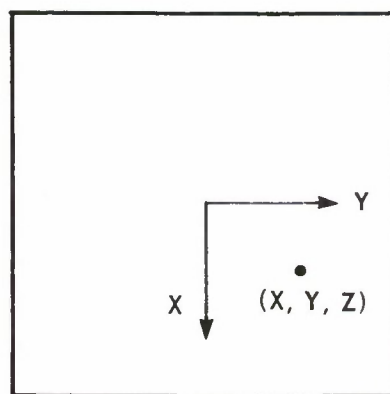
Measuring the coordinates of the image on the photographs gives the ratios

$$\frac{Z}{Y} \quad \text{and} \quad \frac{X}{Y}$$

Inspection of the photographs establishes the quadrant of (X,Y,Z) .



SIDE
VIEW



TOP
VIEW

Fig. 25. Photographic Representation of a Joint Center

APPENDIX A (cont.)

The distance of the photographic image from the center or origin of a photograph determines the angle between the corresponding camera axis and the line from the camera lens to (X,Y,Z).

Considering the side camera, a distance l_a from the center or origin on the photograph to the joint-center corresponds to a length $\frac{l_a}{l_s} L_s$ on the

perpendicular calibration grid, and hence to an angle whose arctangent is $\frac{l_a}{l_s} \frac{L_s}{C}$ (See Figure 26).

This yields the equation:

$$\sqrt{\frac{Y^2 + Z^2}{X_c - X}} = \frac{l_a L_s}{l_s C} \quad \text{EQ 2}$$

Use of this equation with the ratios $\frac{Z}{Y}$ and $\frac{X}{Y}$ yields

$$\sqrt{\frac{\left(\frac{X}{Y}\right)^2 (Y)^2 + \left(\frac{Z}{Y}\right)^2 (Y)^2}{X_c - \left(\frac{X}{Y}\right) (Y)}} = (\text{Sign of } Y) \left(\frac{l_a L_s}{l_s C} \right)$$

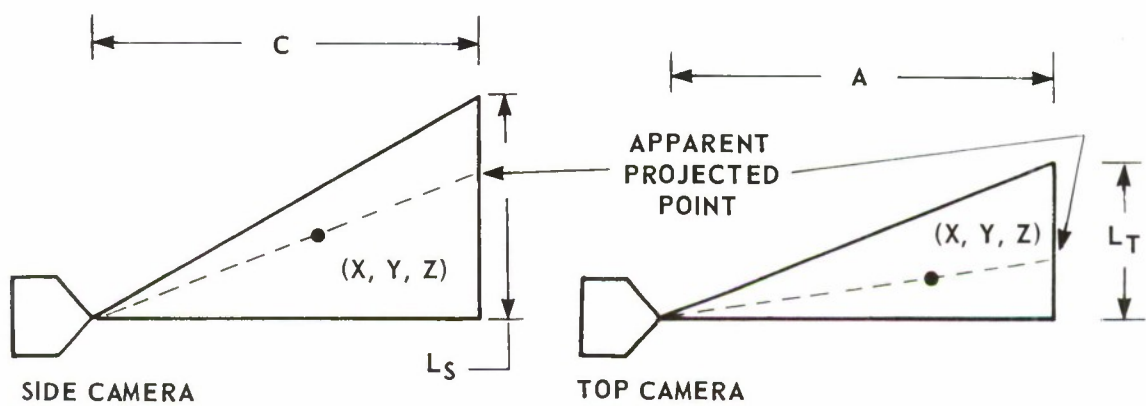


Fig. 26. Apparent Location of a Joint Center

APPENDIX A (cont.)

which yields a quadratic equation

$$Y^2 \left[\left(\frac{X}{Y} \right)^2 + \left(\frac{Z}{Y} \right)^2 \right] + Y \left(\frac{X}{Y} \right) \frac{l_a l_s}{l_s c} - X_c \left(\frac{l_a l_s}{l_s c} \right) = 0$$

Hence Y can be determined and multiplying the ratios of $\frac{X}{Y}$ and $\frac{Z}{Y}$

by Y yields X and Z. Similar methods are applicable to the top view if a check on the results is desired.

APPENDIX B

STATISTICAL DESIGN

An initial statistical approach for accomplishing the validation of the man-model is presented here. This approach, involving tests of hypotheses on means, is considered to be consistent with the amount of data gathering and analysis obtained during Phase I of the Cockpit Geometry Evaluation Program. The knowledge and experience obtained in applying this approach will permit development of more elaborate multivariate analysis of variance methods in later phases.

Basic assumptions and descriptions for the statistical analysis are presented in Section B-1. The proposed hypothesis tests and methods of performing them appear in Section B-2.

B-1 COMPARISON OF HUMAN AND MAN-MODEL MOTION

It is assumed that the human motion required to perform a specified task can be adequately defined by a finite number of points on the trajectories described by well-chosen anatomical locations as the motion is performed. While the trajectories are described in three-space, the X-coordinates of the trajectory sample points, for instance, will be fixed at the outset for each task. Hence, deviations between trajectories will be two-dimensional.

B-1 COMPARISON OF HUMAN AND MAN-MODEL MOTION (cont.)

The performance of a task, then, will be defined by a vector of trajectory sample points

$$(X_i, Y_j(X_i), Z_j(X_i))$$

where the X_i are preselected for each task and $j = 1, 2, \dots, k$ is the index of anatomical location. This method of task characterization is illustrated in Figure 27. The $Y_j(X_i)$ and $Z_j(X_i)$ are assumed to be normal random variables. To simplify notation, the following redefinition of coordinate values is made:

$$u_1 = Y_1(X_1)$$

$$u_2 = Z_1(X_1)$$

$$u_3 = Y_2(X_1)$$

$$u_{2k+1} = Y_1(X_2)$$

etc.

In this notation, the vector describing the performance of a particular task is the column vector $\vec{u} = (u_i)$. Since it is deviations between task performances that are of interest, a sample of column vectors $\{\vec{u}_k\} = \{(u_{ik})\}$ are examined where $k = 1, 2, \dots, N$ refers to the k^{th} repetition of the task by a particular individual.

The trajectories described by the mathematical model in performing the task will be defined by the column vector $\vec{\mu} = (\mu_i)$ where the μ_i

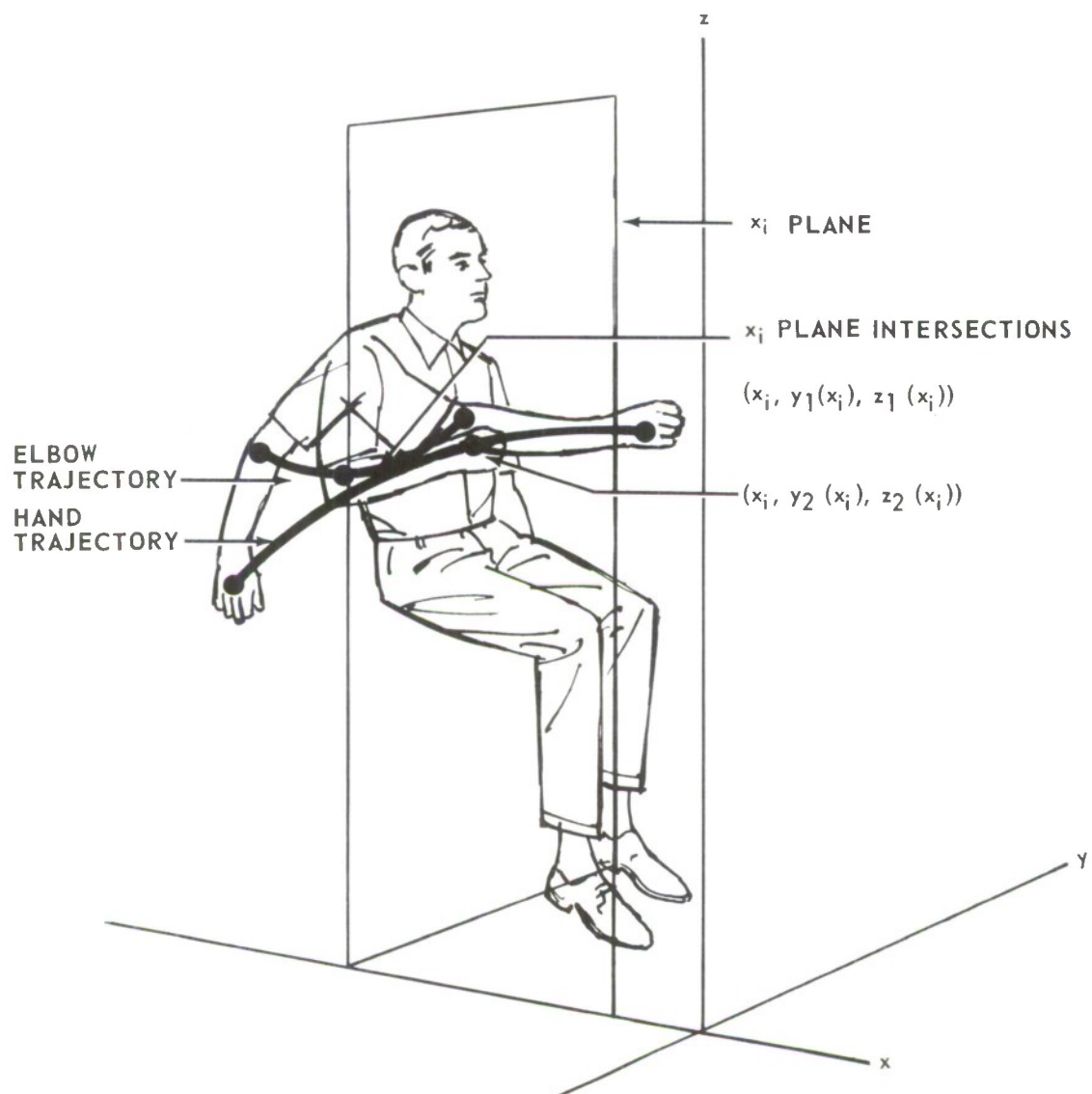


Fig. 27. Task Characterization

B-1 COMPARISON OF HUMAN AND MAN-MODEL MOTION (cont.)

corresponds to the u_i . The hypothesis is that the sample vectors $\{\vec{u}_k\}$ for a particular individual performing a particular task are samples drawn from a multivariate normal population with mean $\vec{\mu}$ and covariance matrix Σ . That is, one hypothesizes that the man-model performs the mean motion of the individual in executing the task.

The points representing the intersection of the sample trajectories and the man-model trajectories with an X_1 plane for a hypothetical task are shown in Figure 28.

B-2 STATISTICAL ANALYSIS

As previously stated, the hypothesis to be tested is that the man-model represents the mean performance of a task by the individual corresponding to the model. One might attempt to accomplish this by testing the set of hypotheses

$$H_{oi} : E^{u_i} = \mu_i$$

However, this set of hypotheses would not alone lead to any conclusions about the model since one would very probably accept some H_{oi} and reject others. To reach a conclusion a single hypothesis is needed involving the entire vector u . One way of accomplishing this is by examining the random variable

$$w = \sum_i (u_i - \mu_i)$$

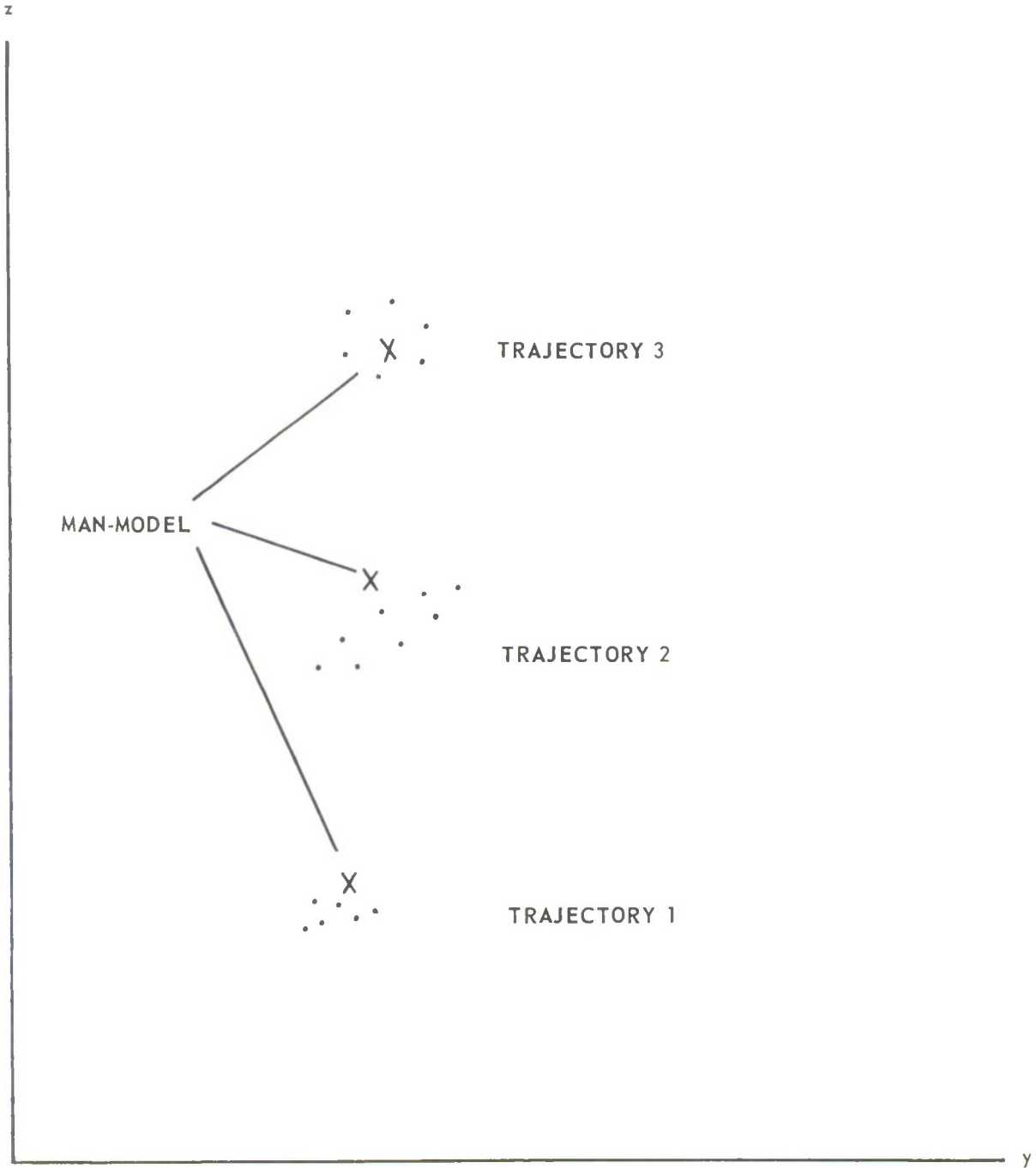


Fig. 28. Example of Points in the X_i Plane

which has a one-dimensional normal distribution with mean zero under the assumption of normally distributed u_i with means μ_i . Note, however, that a great amount of cancellation can take place among the terms of the sum w , hence it can be expected that hypothesis tests involving w will be very weak.

To avoid this difficulty, a much stronger hypothesis is formulated

$$H_{01} \quad ; \quad E \vec{a} \vec{u} = \vec{a} \vec{\mu} \quad \text{for all } \vec{a} \in A$$

where $\vec{a} = (a_i)$ is a column vector and A is the set of all such column vectors with positive a_i . That is, the hypothesis is that all linear combinations

$$w_a = \sum_i a_i u_i$$

of the coordinates u_i with positive a_i have expected value

$$w_a = \sum_i a_i \mu_i$$

Then cancellations between terms which are significant for one vector a will not be significant for a different \vec{a} and if all possible \vec{a} with positive a_i are permitted, the effect of cancellation will be eliminated.

Fortunately, it is not really necessary to examine all vector product

a u. H_0 can be tested by the decision rule

$$\text{Accept } H_0 : E \vec{u} = \vec{\mu} \quad \text{if } F \equiv \frac{(N-p)T^2}{p(N-1)} \leq F_\alpha ; p, N-p$$

where

$$T^2 = N(\vec{u} - \vec{\mu})^T S^{-1} (\vec{u} - \vec{\mu})$$

N = size of the sample $\{u_k\}$, p = number of coordinates in the vector \vec{u} ,

$$\vec{u} = (\bar{u}_i), \bar{u}_i = \frac{1}{N} \sum_{k=1}^N u_{ik}, S = [s_{ij}] = \left[\frac{1}{N-1} \sum_{k=1}^N (u_{ik} - \bar{u}_i)(u_{jk} - \bar{u}_j) \right]$$

and

$$P [F \leq F_\alpha ; p, N-p] = 1 - \alpha$$

where F has the F distribution with p and $N-p$ degrees of freedom.

Note that necessarily $N > p$. This is not unexpected since this is an attempt to compute information about p parameters $\mu_i = E u_i$ and p^2 co-variance σ_{ij} for the parameter matrix Σ . However, it does imply that the planes $X - \mathbf{X}_i$ must be carefully chosen to keep sample sizes at a practical level. Only planes where the greatest deviation between the model and humans is expected might be chosen. Thus the hypothesis that the man-model performs the mean motion of a particular individual performing a particular task can be tested by computing a single number and comparing it with a standard table of the F -distribution.

(NOTE: In some tables of $F_{\alpha; p, N-p}$, $N-p$ is referred to as "degrees of freedom for lesser mean square" while p is termed the "degrees of freedom for greater mean square".)

A caveat is required with respect to inversion of the matrix S . If the motion of a particular anatomical location is strongly constrained, a strong correlation will appear between the random coordinates $Y_j(X_i)$ and $Z_j(X_i)$ for that trajectory, i.e., a one-dimensional rather than the postulated two dimensional variation will occur. An example of such a case is shown in Figure 29 below and to a lesser extent in Figure 28.

Such correlation could result in an ill-behaved S matrix which would be difficult to invert. This difficulty is most easily circumvented by omitting either the $Y_j(X_i)$ or the $Z_j(X_i)$ sample values from the u vector (thereby restricting the sample to a projection of the total variation for the location concerned). However, more elaborate, coordinate transformational techniques can no doubt also be devised.



Fig. 29. Correlation Between Sample Points

The hypothesis test proposed is expected to provide a useful tool for initial statistical comparison of human motion and man-model simulation. This statistical approach also appears to be the most rewarding with respect to obtaining the knowledge and insight required to devise more elaborate statistical methods for the man-model validation.

The main defect of the proposed test is the requirement that the sample size be greater than the dimension of sampled vectors. This defect can be partially offset by sampling trajectories only at points of maximum variability or at points where the variability is most critical to definition of the man-model.

It is expected that results of the initial analysis will permit overcoming this defect by derivation of analytical methods for combining data in such a way that statistical parameters are lumped together, thereby reducing the required sample size.

SUBJECT: W.E.S. TASK: 1 TARGET (CALCULATED): 6.9, 27.5, 13.2 TARGET (MEASURED):

[illegible]

APPENDIX
TYPICAL SUBJECT DATA

D162-10129-1
85 & 86

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13. ABSTRACT <p>A baseline 23-joint variable link length man-model has been developed. Three-space movement of the upper torso has been developed utilizing mathematical and computer techniques. Rigerous validation criteria developed held that the model must closely simulate the joint movement paths and the maximum reach envelopes of any sized human operator workstation. Human joint movement data was obtained using a multiple camera technique. Seven seated subjects repeatedly performed movements in an open space and in a multimission flight simulator. A rigorous statistical analysis compared the synthesized arm joint locations of the man-model with those of the subjects. The comparisons were made at joint locations of each task where the greatest discrepancies between the model and the subjects were expected to occur. In general, the results indicated that statistical differences occur; however, practically, they appear negligible. Therefore, the concept of a mathematical man-model appears feasible and future efforts should continue to refine and improve the model as well as the validation criteria and methods. (U)</p> <p>The distribution of this abstract is unlimited.</p>		

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Validation Man-model Human joint movement Computer model						